An assessment of UK bioenergy production, resource availability, biomass gasification and life cycle impacts

Adams, Paul

Award date:
2011

Awarding institution:
University of Bath

Link to publication

AN ASSESSMENT OF UK BIOENERGY PRODUCTION, RESOURCE AVAILABILITY, BIOMASS GASIFICATION, AND LIFE CYCLE ENVIRONMENTAL IMPACTS

Paul William Richard Adams

A thesis submitted for the degree of Doctor of Philosophy

University of Bath
Department of Mechanical Engineering
May 2011

Signed……………………………………………………………………………………………….

ABSTRACT

Energy use and the environment are inextricably linked and form a key role in concerns over sustainability. All methods of energy production involve resource uncertainties and environmental impacts. A clear example of this is the use of fossil fuels which present three main problems, being: finite resources; significant contribution to environmental pollution; and reliance on imports. Hence there is a clear need to reduce the use of fossil fuels for energy. Bioenergy has the potential to both displace fossil fuels, and reduce the effect of climate change by sequestering carbon dioxide during the production of biomass. It is also possible that bioenergy can reduce the UK's dependence on energy imports and boost the rural economy.

This thesis provides an interdisciplinary assessment of bioenergy production in the UK. Due to the complexities of bioenergy systems several appraisal methods have been used. An initial study examined the barriers to and drivers for UK bioenergy development as a whole. It was found that for projects to be successful, bioenergy schemes need to be both economically attractive and environmentally sustainable. A biomass resource assessment was then completed using the South West of England as a case study. This demonstrates that bioenergy can make a useful contribution to the UK's energy supply, due to the diverse range of biomass feedstocks currently available. However a range of barriers and constraints will need to be overcome if the UK is to reach its bioenergy potential.

To assess the potential environmental impacts of bioenergy production different case studies were selected. Life cycle assessment is widely regarded as one of the best methodologies for the evaluation of burdens associated with bioenergy production. This was applied, alongside net energy analysis, to a small-scale biomass gasification plant which uses wood waste as a feedstock. As an alternative biomass source, the perennial energy crops Miscanthus and Willow were also assessed. Several different scenarios of biomass cultivation, transportation, and energy conversion were then compared, to assess the potential environmental impacts.

Biomass gasification offers good potential for reducing fossil fuel use and climate change impacts. Nonetheless embodied energy in the construction phase can be high and other impacts such as particulate emissions, ecotoxicity and land use can be important. Therefore environmental benefits are maximised when both electricity and heat are utilised together, and when waste is used as feedstock. The ultimate applicability of biomass gasification is restricted by the quantity of feedstocks that can be made available for conversion. Perennial energy crops offer several advantages over annual crops including more positive energy balances and reduced agro-chemical inputs. However their cultivation needs to be carefully sited to avoid issues of land use change and the displacement of food crops.

This study shows that each bioenergy production pathway needs to be assessed using a range of appraisal techniques, which include: biomass resource assessment, technical and economic feasibility, life cycle assessment and net energy analysis. It concludes that biomass gasification CHP offers an alternative to fossil fuel generation but more technical knowledge is required in the UK if it is to become widely used for biomass energy.

ACKNOWLEDGEMENTS

This research on bioenergy at the University of Bath has been supported by a research studentship from the Environment Agency, Great Western Research (GWR) and the University of Bath; jointly supervised by Professor Geoffrey Hammond and Dr Marcelle McManus. Additional support on bioenergy policy and project management was provided by Matt Georges and Jo Marchant at the Environment Agency.

The author is extremely grateful to the support offered throughout the PhD research by both Dr McManus and Prof Hammond. A special thank you is extended to Marcelle, who has provided endless advice, guidance, support and direction throughout, and from whom I have learnt an incredible amount (thanks also for your patience!). I would also like to thank Dr William Mezzullo for helping me settle into the sustainable energy research team (SERT) and providing various support, information and in-depth discussions about bioenergy. All of SERT have made this PhD an enjoyable experience. Additional thanks is owed to Dr Stephen Allen, Dr Gemma Cranston, Dr Hassan Harajli, Dr Craig Jones, Jon Norman and Carly Whittaker for various advice on energy, the environment, life cycle assessment, bioenergy, and the occasional, coffee, beer, game of squash, tennis or football. It's been a great pleasure to work in such a great team.

Sustainable Energy Ltd, and in particular Dr Gabrielle Gallagher, deserve a special mention for providing invaluable data and information on their biomass gasification plant. Without the interest and enthusiasm of Dr Gallagher much of this research would not have been possible. Thank you also to all of the companies, academics and consultancies who have provided data for this thesis, there are too many to mention here.

A debt of gratitude is owed to all the external respondents to the barriers and drivers to bioenergy online survey (Adams *et al*., 2011). This includes individuals and organisations across the UK bioenergy industry: farmers, suppliers, civil servants, electricity companies, developers, engineers, consultants, policy makers and various others. Many contributed willingly even when they did not agree with every aspect of this demonstration. Their names remain anonymous as agreed at the outset of the trial.

Many thanks to the farmers who provided information and farm management data on the growth of perennial energy crops: Tim Barton (Wadswick Farm, Corsham, Wiltshire), Gary Mead (Holt Farms, Blagdon, Somerset) and Andrew Hughes, (Long Ashton Research Farm, Bristol), and other farmers I have met at various bioenergy events and conferences over the last few years.

And last but certainly not least all of my friends and family. In particular, Daniel Narayanan for providing valuable knowledge of engineering, energy systems, and taking the time to read my work. Mum, Dad and my brother James for being such an amazing loving family, providing support throughout and reading my thesis. And Sophie, who provided me with love, laughter, support and the encouragement to finish.

I am eternally grateful to everyone who has made this thesis possible. It was extremely motivating to have the opportunity to work with such a wide variety of people and organisations from academia, agriculture, consultancies, Government and industry.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY, ABBREVIATIONS AND NOTATIONS

~	Approximately
1,4-DB eq.	1,4-DB equivalent describes the toxicity potential a given type and amount of toxic emission may cause, using the functionally equivalent amount or concentration of 1,4-Dichlorobenzene (para-dichlorobenzene, an organic compound with the formula $C_6H_4Cl_2$) as the reference
AD	Anaerobic Digestion - the biological reaction for biogas production (see definition in Chapter 2)
AONB	Area of Outstanding Natural Beauty
BERR	The UK's 'Department for Business, Enterprise and Regulatory Reform'; formerly the 'DTI' (see below)
BGP	Biomass Gasification Plant
Biogas	The by-product of AD. This gaseous fuel is a mixture of methane, carbon dioxide and other trace elements
Biogenic	Produced or originating from living organisms, e.g. biogenic carbon
Biowaste	Organic waste that is putrescible, i.e. liable to decay or spoil
BSSA	British Stainless Steel Association
C	Carbon
Capacity Factor	The average power produced by an electrical generator divided by the maximum power that could be produced
CBA	Cost Benefit Analysis
CED	Cumulative Energy Demand
CH_4	Methane
CHP	Combined Heat and Power
CO_2	Carbon dioxide
CO_2 eq.	CO_2 equivalent describes the global warming potential a given type and amount of greenhouse gas may cause, using the functionally equivalent amount or concentration of carbon dioxide (CO_2) as the reference.
CV	Calorific Value (see definition in Chapter 2)
DALY	Disability Adjusted Life Years (see definition in Chapter 3)
db	Dry basis
DECC	The UK's 'Department for Energy and Climate Change'
DEFRA	The UK's 'Department for Environment, Farming and Rural Affairs'
Degree days	A degree day is a measure of heating or cooling (see Carbon Trust, 2010)
Delivered energy	Following their extraction and processing, natural primary energy resources are converted into suitable forms of fuel and electricity which can be used by consumers. These forms of energy are together known as delivered energy
DTI	The UK's 'Department of Trade and Industry', now 'BERR'
e	electricity (as used when expressing energy, e.g. kWh_e)
EAF	Electric Arc Furnace
ECS	Energy Crops Scheme
EFG	Entrained Flow Gasification (see references in Chapter 2)
EGR	Energy Gain Ratio (see definition in Chapter 3)
EIA	Environmental Impact Assessment

Embodied energy	The total (direct and indirect) energy requirement a product or activity at the point of either production or delivery to the end-user. Energy requirements are traced back to their naturally occurring form and quantified in terms of enthalpy
Enthalpy	Enthalpy is a measure of the total energy of a thermodynamic system (see Allen, 2009)
EPP	Energy Payback Period (see definition in Chapter 3)
ERA	Ecological Risk Assessment
ERE	Energy Requirment for Energy (see definition in Chapter 3)
EU	European Union
Extractive metallurgy	The practice of removing valuable metals from an ore and refining the extracted raw metals into a purer form
FC	Forestry Commission
Fe eq.	Fe equivalent describes the metal resource depletion potential a given type and amount of metal consumption may cause, using the functionally equivalent amount or concentration of iron (Fe) as the reference
FIT	Feed-in Tariff (see DECC, 2010a)
Functional Unit	The unit of comparison in LCA that assures that the products being compared provide an equivalent level of function or service (see Chapter 3)
GCV	Gross Calorific Value (see Chapter 2 for definition)
GER	Gross Energy Requirement (see Chapter 3 for definition)
GHG	Greenhouse gas
GJ	Giga Joule (=1,000MJ)
GWh	Gigawatt-hour (=10^3 MWh)
GWP	Global Warming Potential
h	hour (also 'hr')
ha	hectare (=10,000m^2)
HHV	Higher Heating Value (see Chapter 2 for defnition)
HTU	Hydro thermal upgrading
HP	Horse Power (1.34HP~1kW)
ISO	International Organization for Standardization
K	Potassium
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt-hour (= 3.6MJ)
LCA	Life Cycle Assessment (see Chapter 3 for definition)
LCI	Life Cycle Inventory (see Chapter 3 for definition)
LCIAM	Life Cycle Impact Assessment Methodology (see Chapter 3 for definition)
LHV	Lower Heating Value (see Chapter 2 for definition)
Load Factor	The ratio of average load to peak load over a period
LUC	Land Use Change
mc	Moisture Content (see Chapter 2 for definition)
Metallurgy	The procedures used in extracting metals from ore, as well as to the processes related to metals purification and alloy production.
MJ	Mega Joule (= 0.278kWh)
mol.	The mole is a unit of measurement for the amount of substance or chemical amount

MW	Mega watt
MWh	Megawatt-hour (=10^3 kWh)
N	Nitrogen
NCV	Net Calorific Value (see Chapter 2 for definition)
Nm^3	Cubic metre of gas at standard condition for temperature and pressure
NO_x	Generic term for the mono-nitrogen oxides NO and NO_2 (nitric oxide and nitrogen dioxide). They are produced from the reaction of nitrogen and oxygen gases in the air during combustion, especially at high temperatures
odt	Oven dried tonne (used to decribe biomass which has a zero moisture content)
P	Phosphorus
PAF	Potentially affected fraction (see Goedkoop *et al.*, 2000)
PDF	Potentially disappeared fraction (see Goedkoop *et al.*, 2009)
PJ	Peta Joule (=10^6 GJ or 10^9 MJ)
Primary electricity	Electricity generated directly from the applicable resource, such as wind, solar, and hydro systems
Primary energy	Consists of the amount of energy available in resources in their natural state, such as coal, natural gas, oil and uranium deposits in the ground
Producer gas	Gas produced from gasification (also known as 'syngas' or 'wood gas')
RHI	Renewable Heat Incentive
ROC	Renewable Obligation Certificate
RTFO	Renewable Transport Fuel Obligation
SE	Sustainable Energy Ltd
Secondary electricity	Electricity derived from a primary source, such as through the combustion of a fossil fuel or biomass
SO_x	Sulfur oxide
SRC	Short rotation coppice
Syngas	Synthetic gas (see 'Producer gas')
t	Tonne
TJ	Tera Joule (=10^3 GJ or 10^6 MJ)
th	Thermal or heat (as used when expressing energy, e.g. MJ_{th})
tkm	Tonne-kilometre
UEL	Useful economic lifetime
Useful energy	Consumers use fuels and electricity in appliances, equipment, etc. to provide heat, light, motive power, etc. Such energy is collectively known as useful energy
VOCs	Volatile organic compounds
wb	wet basis
WID	Waste Incineration Directive
wt.	weight
WU	Work units
yr	Year

CHAPTER 1. INTRODUCTION

This chapter outlines the background to the thesis, reasons why the study was undertaken, its aims, research objectives, why the case studies were chosen and the way in which the thesis has been organised.

1.1 BACKGROUND

Modern human society is increasingly reliant on energy to maintain the lifestyles to which we have become accustomed. Humans have developed a range of energy conversion technologies to provide a diverse array of services which includes electricity, heat, and transportation. Over the past few decades the sustainability of humankind's activities has become increasingly questionable. An increased awareness of environmental issues and externalities has evolved in the context of sustainable development. For humans, sustainability is the potential for long-term preservation of well being, which has environmental, economic, and social dimensions. Sustainable development incorporates these three dimensions and can be defined as the process by which sustainability (the capacity for continuance) is achieved (Parkin, 2000). According to Hammond (2004) and Parkin (2000) the concept came to prominence with the publication of 'Our Common Future' in 1987, which viewed sustainable development as balancing the 'three pillars' of economic and social development with environmental protection (WCED, 1987). Energy consumption plays a fundamental role in human development; it powers economic growth, provides society with many of its needs, but also impacts upon the environment. Therefore an interdisciplinary approach is required when assessing energy systems (Allen, 2009; Thornley *et al.*, 2009a).

1.2 ENERGY AND THE ENVIRONMENT

Energy (use) and the environment are inextricably linked and form a key role in concerns over sustainability. Most methods of energy use involve resource uncertainties and environmental impacts on a local, regional and global scale (Hammond, 2004). A clear example of this is the consumption of fossil fuels in the European Union (EU) which creates several problems. Firstly, fossil fuels are considered to be a finite resource for which the demand is increasing (IEA, 2009). Secondly, the use of fossil fuels makes a significant contribution to environmental pollution through, among other impacts, the emission of greenhouse gases (GHGs) and air pollutants (DTI, 2007; IPCC, 2007). Thirdly, roughly half of the primary energy consumed in the EU is supplied by imports and this percentage is expected to increase to 70% by 2030, assuming no significant changes in policies take place (European Commission, 2001).

Energy use in the UK is dominated by fossil fuels which account for 90% of the energy supply and 96% of carbon dioxide emissions (DECC, 2009a). The UK is heavily dependent on gas and coal for heat and power and oil for transport, and is increasingly a net importer (DECC, 2009a). Using fossil fuels contributes significantly to GHG emissions and they are non-renewable, finite, resources. These problems are complicated by the fact that these fuels are unevenly distributed around the world and often come from politically unstable countries (IEA, 2009). Consequently there is a rapidly growing interest in finding new renewable sources of energy which do not pollute the earth's atmosphere, and which provide more secure and sustainable energy supplies.

Renewable energy is of growing importance in addressing environmental and security concerns over fossil fuel use. Bioenergy is considered to be one such possible energy source. Wood and other forms of biomass including energy crops and agricultural, forestry, and industrial wastes are some of the main renewable energy resources available (Bridgwater, 2004). Biomass can be used as a substitute for fossil fuels and may reduce the dependence on imports and/or the carbon dioxide emissions. Other benefits of bioenergy could include enhancing the rural economy and more localised energy production. However, all forms of energy production give rise to environmental penalties or 'side-effects', regardless of whether it is carbon-emission related or not; but these vary depending on the source of energy and methods of conversion (Hammond, 2000). It has therefore been identified that there is a need to better understand the biomass resource available and the potential environmental impacts associated with bioenergy production and use in the UK. There is also a need to compare, where possible, the potential impacts of bioenergy production with the fossil fuel-based energy sources that may be substituted for biomass-based sources.

1.3 BIOMASS AND BIOENERGY

Biomass is the biodegradable fraction of plant-based products, wastes and residues, derived from agriculture, forestry and industry (European Commission, 2008). The term bioenergy describes energy (heat, electricity and transport fuels) derived from biomass feedstocks. Chapter 2 provides further description of bioenergy systems and their related terminology.

The diversity of applications for bioenergy is one of the most attractive features of this form of energy. There is a wide variety of plants, trees and residues which can be used to produce energy. Biomass feedstocks can be converted into several forms of useful energy including liquid biofuels for transport and solid biomass for heat and electricity generation. It is increasingly recognised globally that plant-based raw materials will play an important role in providing alternatives to fossil reserves as feedstocks for industrial production, addressing both the energy and non-energy sectors including chemicals and materials (European Commission, 2004).

Bioenergy has generated significant interest for a variety of reasons. On first inspection bioenergy appears to be carbon-neutral (the carbon it emits to the atmosphere when burned is offset by the carbon that the plants absorb from the atmosphere when growing), it is a renewable source (fresh supplies can be re-grown), and plants can be cultivated in many different environments. On closer inspection it becomes apparent that the reality is more complex. One use of bioenergy is not the same as another and each must be considered individually. An assessment which includes a variety of criteria is therefore necessary. This assessment should include resource availability, GHG and energy balances, environmental impacts, socio-economic, political and regulatory issues (Royal Society, 2008; Thornley *et al.*, 2009a).

The use of bioenergy in Europe is expected to increase significantly over the next decade due to EU targets for reducing carbon emissions and increasing the use of renewable energy (European Commission, 2009). Expanding bioenergy production is likely to increase the demand for dedicated energy crops, which can cause changes in land-use and intensification of farming. The selection of land on which to grow the feedstocks is a key component of the ability of bioenergy to deliver sustainable solutions. Potential issues include inputs of artificial fertilisers, water use and quality, the conservation of biodiversity, and the displacement of food crops. Agricultural production and biomass conversion techniques will determine energy use, GHG balances and other impacts.

Different conversion technologies exist which allow biomass feedstocks to be converted into useful forms of energy (see Chapter 2). Biomass gasification is one such technology which adds worth to low or negative value feedstock by converting them to marketable fuels and products (Bridgwater, 1995). A good example of this is the gasification of waste to produce heat and power, where the alternative could be landfill, incurring landfill tax, a gate-fee and transportation costs. Gasification is considered to be one of the most promising technologies in biomass applications (IEE, 2007). Advantages can include higher efficiencies compared to combustion, perspectives in fuel synthesis, and application to a wide range of biomass feedstocks (Knoef, 2005). However, current utilisation of biomass gasification is low and so far has not achieved commercial status in the UK. It has therefore been identified that there is a need to increase the knowledge of biomass gasification.

Another conversion technology which offers good potential for the South West region and the UK is anaerobic digestion (AD). This technology is more developed, better understood and has reached commercial viability in the UK. A recent study by Mezzullo (2010) assessed the potential for AD in the South West region. Therefore AD will not be assessed in detail but some findings from the Mezzullo (2010) study will be used in Chapters 9 & 10.

1.4 BIOENERGY-RELATED POLICIES AND TARGETS

At the national, regional and global levels there are three main political drivers for the development of bioenergy: climate change, energy security and rural development (DEFRA, 2007a). Climate change is now near the top of the political agenda both in the UK and abroad, with the UK Government setting targets to reduce greenhouse gas (GHG) emissions by 80% over 1990 levels by 2050, with identifiable progress being made by 2020 (UK Parliament, 2008a). The UK has also agreed to an EU target to produce 15% of the UK's energy from renewable sources by 2020 (UK Parliament, 2008b). The UK Biomass Strategy proposed to increase the use of biomass for heat, electricity and biofuels, and outlines the potential UK supply of feedstocks up to 2020 (DEFRA, 2007a). In addition, the UK Renewable Energy Strategy indicates that bioenergy will play an important role for renewable electricity, heat and transportation energy (DECC, 2009b).

If bioenergy is to deliver the promised reduction in greenhouse gas (GHG) emissions, it must be developed in a sustainable way (Thornley *et al.*, 2009b). Government policy is therefore required at a national and international level to promote sustainable bioenergy systems that deliver real carbon savings on a lifecycle basis. GHG emissions and other environmental impacts arise from each stage in the supply chain from feedstock production and transport to conversion, distribution and end use. A detailed life cycle assessment of net energy and GHG balances, but also other environmental impacts, is therefore required (Royal Society, 2008). However, there are few studies which assess a range of potential environmental impacts, as most focus on energy and carbon assessment.

Demand for oil and gas is rising and the UK is increasingly reliant on imported energy supplies, hence bioenergy may offer a good opportunity to increase energy security. By producing home-grown bioenergy the UK can help meet more of its own energy requirements from domestic sources. This could help reduce dependency on oil and gas supplies from politically unstable regions. To increase energy security, biomass feedstocks need to be produced sustainably from reliable sources, minimising the distance over which they are transported. Growing feedstocks close to the point of production is usually considered important in order to maximise energy security and minimise transport emissions (DEFRA, 2007a). Hence one aim of this thesis is to assess the environmental impacts which may arise as a result of an increase in UK energy crop production.

The establishment and growth of energy crops for bioenergy gives farmers a new market to sell their produce. New workers are also required to help utilise existing biomass resources (RCEP, 2004; Thornley *et al*., 2008). For example, forestry management can contribute significantly to biomass production through improved utilisation of existing forestry resources. Rural development is therefore an integral part of the bioenergy industry. Entrepreneurial farmers are likely to produce energy crops provided they are profitable and there is a guaranteed market. However, currently the uptake of energy crops has been low despite subsidies such as the energy crop scheme (Adams *et al*., 2008, Sherrington *et al*., 2008). Other opportunities for farmers include the utilisation of waste through technologies such as anaerobic digestion (DEFRA, 2010a).

Government-set regulations put in place in the past years have created an interest in producing energy from biomass. Electricity generation from renewable sources has been incentivised via the introduction of the Renewable Obligation. This is an obligation for UK electricity suppliers to source a fixed percentage of their electricity from renewable sources (Ofgem, 2009). More recently a feed-in tariff (FIT) and renewable heat incentive (RHI) have been launched where householders and organisations are paid a fixed rate if they use biomass and other low carbon sources to generate electricity and heat respectively (DECC, 2010a; DECC, 2011). Other Government-led initiatives include the deployment of the Renewable Transport Fuel Obligation (RTFO) (DfT, 2008).

There are a number of subsidies available within the UK to help grow feedstocks for bioenergy processes. These are mainly aimed at farmers within the UK for growing biofuels crops. These include the Single Payment, the Entry Level Environmental Stewardship Scheme and the Energy Aid Payment Scheme (EAC, 2008). A market 'push' incentive called the Bioenergy Infrastructure Scheme helps to develop biomass supply chains from harvest through to delivery to heat and power end-users, providing grants for essential, dedicated equipment such as chippers. Market 'pull' incentives have been provided by grant schemes such as the Bio-energy Capital Grants Scheme, recommended by a Government report issued in 2005 (Gill *et al.*, 2005). Other schemes which have supported the biomass supply chain include the Biomass Heat Accelerator project run by the Carbon Trust, the Low Carbon Buildings Programme, and various initiatives by Regional Development Agencies and the Forestry Commission. Despite these various incentives the uptake of bioenergy in the UK is still relatively low; hence there is a research need to understand what the barriers are to further development.

1.5 AIMS & SCOPE OF THE RESEARCH

This research has been jointly supported by the Environment Agency of England & Wales, the Great Western Research alliance (GWR), and the University of Bath. The Environment Agency's principal aims are to protect and improve the environment, and to promote sustainable development. Their interest in this research was to:

- Obtain a better understanding of the current bioenergy industry in England & Wales by assessing current bioenergy production and use;
- Identify which biomass feedstocks and conversion technologies are likely to be utilised over the next decade and beyond;
- Assess what the possible environmental impacts of an increase in biomass production could be. In particular, what potential effects on the environment an increase in the growth of perennial energy crops could have?
- Assess the potential environmental impacts of the conversion technologies likely to be employed in the future.

Biomass gasification was chosen as the conversion technology (or bioenergy pathway) to assess the potential environmental impacts of. Detailed assessment of more than one conversion technology was beyond the scope of this research.

GWR was established to promote research collaborations between universities and businesses in the South West of England. This research was supported through the ‘sustainability’ theme of the alliance. GWR’s interests in this research focused on assessing the biomass and bioenergy production potential for the South West region. More specifically, GWR wanted to ascertain what contribution bioenergy could make towards the region’s renewable energy supply and targets, and what the environmental effects of increased bioenergy production might be.

A collaborative approach was a useful research partnership as several common aims were identified. However the geographical scope was different with GWR focused on the South West and the Environment Agency covering England & Wales. This difference was overcome as it was agreed with both parties that the research should assess the UK situation, but using the South West in case studies wherever appropriate. This thesis is therefore concerned with bioenergy production and use in the UK, with a particular focus on the South West of England.

At present the UK bioenergy industry is in its relative infancy in comparison to other European countries (IEE, 2009a; Observ’ER, 2007). Various Government policy drivers (outlined in section 1.4), among other reasons (see Chapter 4), are anticipated to increase UK bioenergy production and use significantly over the next decade and beyond (DECC, 2009b). How this increase will occur and what the implications of this could be is less well known. Hence the general aim of this thesis is to distinguish the current UK bioenergy situation, understand how this may develop, and assess what the energy potential and possible environmental impacts of an increase in bioenergy production could be.

To achieve this aim it is necessary to identify what biomass resources are presently available, which conversion technologies are utilised, and what the end-uses are. Another step is to understand how bioenergy in the UK may develop in order to help meet Government targets. From this it is expected that the biomass resources and conversion technologies which are likely to be utilised over the next decade will be better understood. By identifying the potential feedstocks and technologies, specific case studies have been chosen to assess what the potential environmental impacts of this development may be. A further aim is therefore to undertake life cycle assessment (LCA) and net energy analyses case studies of some of the bioenergy systems likely to be exploited up to 2020 and beyond. The chosen case studies focus on the growth of perennial energy crops and biomass gasification (as highlighted in sections 1.3 and 1.4). Further description of why these were chosen is included in Chapter 2 section 4.

1.6 RESEARCH OBJECTIVES AND THESIS STRUCTURE

A range of objectives have been defined to achieve the aims specified above. These objectives are highlighted below alongside how they are addressed within the thesis.

1. **To outline relevant fundamental aspects of different bioenergy systems, describe the relevant terminology, and outline potential gaps in bioenergy research knowledge (Chapter 2)**

Chapter 2 provides relevant information on biomass, conversion technologies, end-uses, and an overview of bioenergy systems. A critical review of previous LCA studies is performed to highlight the research need for a full LCA on the chosen bioenergy pathways. Additional background is also presented on the perennial energy crops (Miscanthus and SRC Willow), biomass gasification, and combined heat and power (CHP), since these were all chosen for the LCA and net energy analysis case studies.

2. **To define the methodologies used in this interdisciplinary assessment of bioenergy production and use (Chapter 3)**

There are four different methodologies used in this thesis defined in Chapter 3. These are: a literature review and stakeholder survey (to assess UK bioenergy development); a resource assessment (to assess the available biomass resource and potential end-use applications); life cycle assessment (LCA) (to assess potential environmental impacts); and net energy analysis (to assess energy potential). Chapter 3 outlines the materials and methods used in the case studies presented in chapters 4 to 10.

3. **To identify the barriers to and drivers for UK bioenergy development, and suggest ways in which the barriers may be overcome (Chapter 4)**

A review of several bioenergy projects is completed to identify the critical success factors and potential barriers to implementation. The main stakeholder groups in the bioenergy supply chain are identified. A stakeholder survey is then undertaken to establish the most important barriers and drivers for each group. The main findings and a discussion of the results are presented in Chapter 4. A number of possible ways in which the Government may address the barriers identified is also included.

4. **To quantify the existing available biomass resource in the South West of England, evaluate how this may change over time, define resource equations for each feedstock, and identify the potential end uses (Chapter 5)**

In Chapter 5 a biomass resource assessment is completed which establishes the currently available resource in the South West region. A clear description of the methodology used and resource equations are defined for each of the biomass feedstocks assessed. The potential contribution towards the region's energy supply and targets is also evaluated.

5. **To assess the potential environmental impacts, using LCA, of an increase in perennial energy crop production (Miscanthus and Willow) for use in bioenergy systems (Chapter 6)**

A LCA of both Miscanthus and SRC Willow is conducted in Chapter 6 following ISO 14040 standard (ISO, 2006a). Life Cycle Inventory (LCI) data are compiled through a range of different sources including consultation with local farmers, literature and Government guidance. This data provides a unique LCI from which the potential environmental impacts are assessed.

6. **To examine the potential life cycle environmental impacts of a biomass gasification plant using LCA and net energy analysis (Chapters 7, 8 & 9)**

A LCA following ISO (2006a) and net energy analysis of a small scale biomass gasification plant (BGP) is completed in Chapters 7 to 9. LCI data are compiled from primary data obtained from a demonstration BGP, and literature where sufficient primary data were not available. Established and up to date impact assessment methods are used to quantify and analyse the potential damages to human health, ecosystems and resource depletion.

7. **To incorporate the analyses of perennial energy crops and biomass gasification to expand the system boundaries and assess the whole life cycle to include crop growth and transportation (Chapter 10)**

In Chapter 10 the results from the LCA of perennial energy crops and biomass gasification are combined along with transportation to produce a LCA of the whole supply chain. Results are compared, where possible, to previous LCA studies available in the literature. A comparison is also made to the potential environmental impacts arising from other energy systems.

This thesis constitutes a variety of separate but inter-linked studies and it is crucial that these are discussed both individually and as a whole. Consequently, key findings are summarised within each chapter, but a discussion of the findings of the chapters is presented as one overall discussion in Chapter 11. As this research is concerned with the South West region (in the context of England & Wales) the discussion chapter includes the implications for this region. Conclusions and recommendations for further work then follow in Chapter 12. Figure 1-1 displays the thesis structure in a schematic representation.

During this research the author has presented some of the research findings at different conferences and published conference papers and a journal article. Where appropriate these publications are referred to at the beginning of the relevant chapter and included in Appendix A.

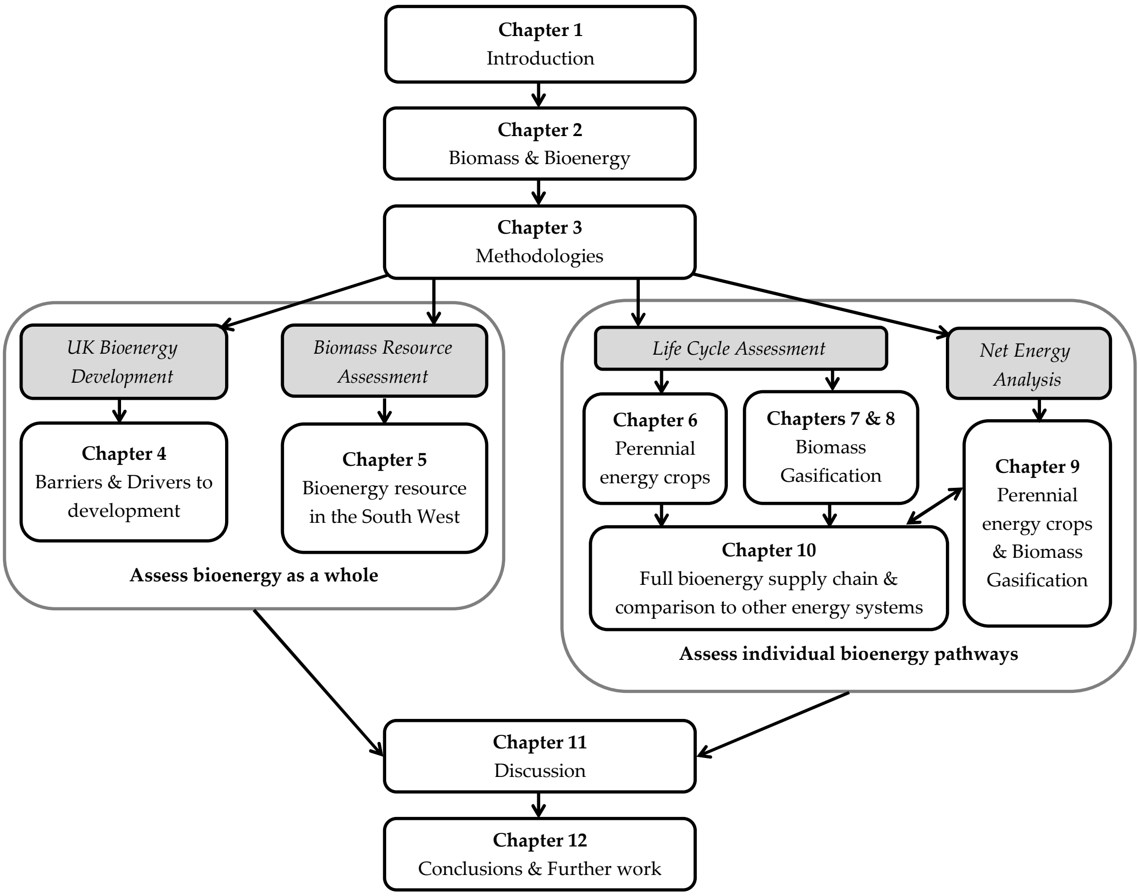


Figure 1-1: Schematic representation of thesis structure

CHAPTER 2. BIOMASS & BIOENERGY

This chapter provides an overview of bioenergy systems and describes some key terminology used throughout this thesis. Descriptions of what biomass is; the different types of biomass available; the various biomass conversion technologies; and potential end-uses are presented. An explanation is then given as to why the life cycle assessment (LCA) and net energy analysis case studies undertaken were chosen in this thesis. Additional information is provided on perennial energy crops, biomass gasification, and combined heat and power (CHP) since these were chosen for the case studies.

2.1 WHAT IS BIOMASS?

2.1.1 Definition of Biomass

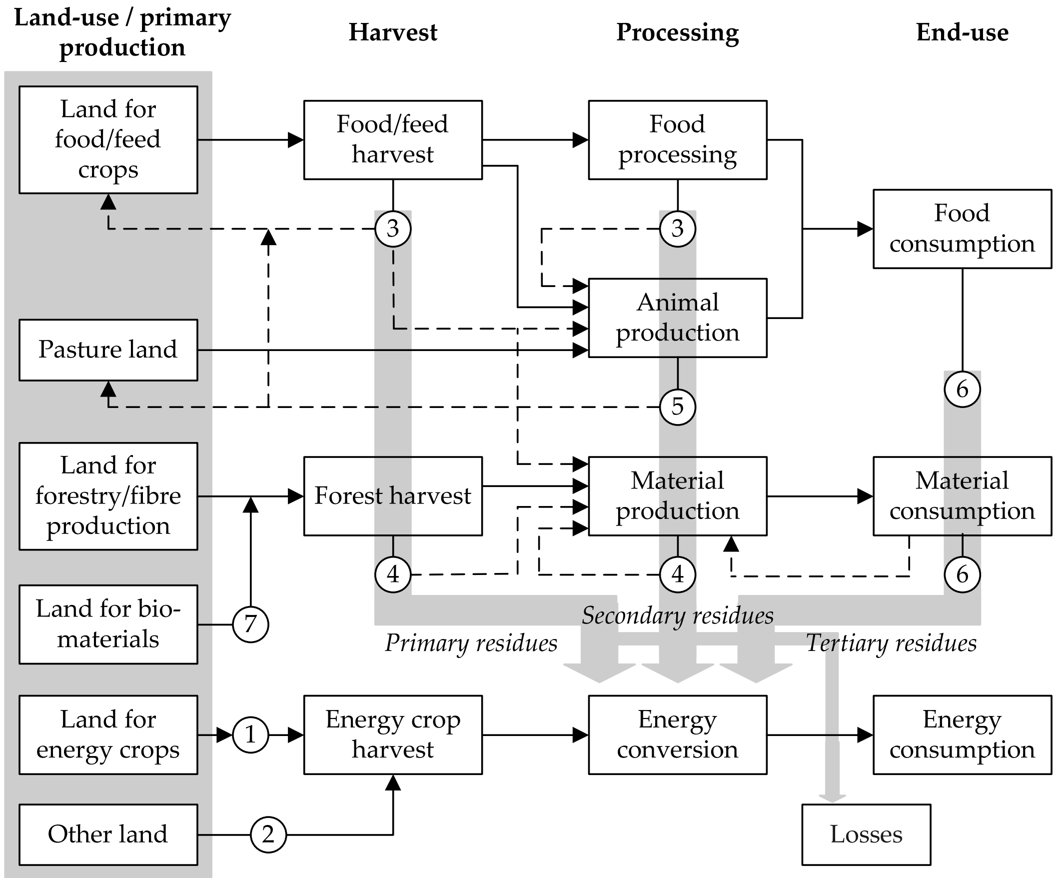
Biomass is a term used for all organic material that stems from plants, which includes crops, trees and algae. Biomass is described in the EU Renewable Energy Directive as: 'the biodegradable fraction of products, waste and residues from agriculture (including vegetal and animal substances), forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste' (EC, 2008). It includes all land- and water-based vegetation, as well as all organic wastes. Biomass is derived from the reaction between carbon dioxide (CO_2) in the air, water and sunlight, via photosynthesis, to produce carbohydrates that form the building blocks of biomass (Ecofys, 2005).

The biomass resource can be considered as organic matter, in which the energy of sunlight driving photosynthesis is stored in chemical bonds. When the bonds between adjacent carbon, hydrogen and oxygen molecules are broken by digestion, combustion, or decomposition, these substances release their stored, chemical energy (McKendry, 2002a). When biomass is processed, either chemically or biologically, by extracting the energy stored in the chemical bonds and the subsequent 'energy' product combined with oxygen, the carbon is oxidised to produce CO_2 and water (McKendry, 2002a). The process is cyclical as the CO_2 is then available to produce new biomass (known as the carbon cycle).

2.1.2 Biomass sources

There are currently a wide variety of biomass resources available in the UK and abroad. The main easily accessible biomass sources derive from agriculture, forestry and industry. Some biomass will be specifically grown for its energy content, so called 'energy crops'. Biomass can also be collected through forestry management and through waste management. Figure 2-1 outlines an overview of various types of biomass flows (adapted from Hoogwijk *et al*., 2003) and highlights the range of potential biomass sources from agriculture, forestry and industrial processes. Within each of these resources there are different biomass types which are outlined in the next section 2.1.3.

Figure 2-1 shows that various different land uses can generate biomass either directly (through dedicated energy crop cultivation) or indirectly (via wastes and residues). Biomass resources can also be derived from different economic processes and end-uses mainly as wastes and residues. Chapter 5 analyses the biomass resources which are currently available in the South West of England.



The black arrows indicate the main product flows, whereas the dotted lines show potential non-energy applications of various residue categories. The grey arrows represent the potential energetic use of the resources (1 = energy crops, 2 = energy crops at degraded land, 3 = agricultural residues, 4 = forest residues, 5 = animal manure, 6 = organic waste, 7 = bio-material).

Figure 2-1: Overview of various types of biomass flows (adapted from Hoogwijk *et al.*, 2003)

2.1.2.1. Biomass from dedicated energy crops

Dedicated energy crops are grown primarily for their energy content, though they may also produce non-energy by-products. Beneficial characteristics of a useful energy crop include high yield, low fossil fuel energy inputs to produce, low nutrient and water requirements, limited contaminants in composition, and low economic cost. Further description of perennial energy crops is provided as background to the LCA case study below.

2.1.2.2. Biomass wastes and residues

Biomass wastes and residues are materials of biological origin arising as by-products and wastes from agriculture, forestry, forest or agricultural industries, and households (Hoogwijk *et al.*, 2003). Unlike dedicated bioenergy crops, biowaste and residues are not produced specifically for use as an energy resource. They are the result of economic activity and production of goods in almost all sectors of the economy. As the production of biowaste occurs anyway, the diversion of biowaste to energy recovery options does not usually increase environmental pressures, however there are some exceptions.

Removal of forestry or agricultural residues from land can reduce carbon storage in carbon pools like soil, dead wood or litter, and can deplete soil nutrients (Forestry Commission, 2007; IEA, 2006; Lattimore *et al.*, 2009). The creation of a market for biomass residues or by-products, giving an additional income stream, can make the production of the main commodity (such as timber) economically more attractive, leading to expansion of this land use, which may have negative environmental impacts (for example, if native forests are replaced) (IEA, 2010b; Lattimore *et al.*, 2009; Royal Society, 2008). However, increased production of wood products may also have positive climatic impacts through substitution of more emission intensive materials (RCEP, 2004). The diversion of biowaste away from landfill to energy recovery can also alleviate some of the environmental pressures associated with landfill, such as methane emissions from anaerobic decomposition of biomass in landfill (Mann & Spath, 2001; DEFRA, 2007c).

2.1.3 Biomass types

Researchers characterise the various types of biomass in different ways (see, for example, FAO, 2004; McKendry, 2002a; Rosillo-Calle *et al.*, 2007). A simple method chosen for this thesis is to define four main types, namely:

- Agricultural wastes & residues
- Energy crops – annual and perennial;
- Forestry – arboricultural arisings, forestry residues, and sawmill co-products;
- Industrial and domestic wastes & residues – commercial and industrial waste streams, landfill gas, municipal solid waste (MSW), sewage sludge, waste fats & oils, and waste wood.

Within this categorisation the different types of biomass can be further divided into individual plants, species, waste streams and so on. Each of these biomass types are characterised in the resource assessment (see Chapter 5), so are not further described here. The choice of which biomass type is used depends upon the end-use, and bio-conversion option of interest (see section 2.2). Equally, the biomass type will determine which conversion processes can be used. Indeed, each type of biomass has different characteristics which make them more (or less) suitable to different conversion technologies.

2.1.4 Biomass characteristics

Biomass is a very versatile feedstock in its morphology and physical characteristics. Hence a number of different bio-conversion technologies have been developed over time to recover energy from a wide variety of different biomass sources. The main physical and chemical properties of biomass feedstocks (of interest during processing as an energy source) relate to (FAO, 2004; Knoef, 2005; McKendry, 2002b):

- Moisture content;
- Calorific value;
- Elemental composition;
- Volatile matter content;
- Other fuel related contaminants like alkalis, heavy metals, etc;
- Bulk density and morphology;
- Ash content and ash composition;
- Cellulose/lignin ratio.

A brief description of each of these biomass properties is discussed here, with an example relating to biomass gasification presented.

2.1.4.1. Moisture content

The moisture content (m.c.) of biomass is defined as the quantity of water in the material expressed as a percentage of the material's weight, two methods are commonly defined (dry basis and wet basis) (FAO, 2004):

$$\text{Moisture}_{\text{dry basis}} = 100 \times \left(\frac{WetWeight - DryWeight}{DryWeight} \right) \qquad \text{(eq. 2.1)}$$

$$\text{Moisture}_{\text{wet basis}} = 100 \times \left(\frac{WetWeight - DryWeight}{WetWeight} \right) \qquad \text{(eq. 2.2)}$$

The m.c. of solid biomass varies widely and is affected by time of harvesting, the location, type and duration of the storage and the fuel preparation. In section 2.2.2.1 the effect of m.c. on the efficiency of combustion is discussed, with higher moisture levels reducing the energy potential of biomass conversion. It is thus important to distinguish the basis on which total moisture is measured. For thermal conversion processes (e.g. gasification) it is preferable to utilise relatively dry biomass feedstock because a higher quality gas is produced, i.e. higher heating value, higher efficiency and lower tar levels (McKendry, 2002a). Natural drying (such as on field) is inexpensive but requires long drying times and does not reduce the m.c. sufficiently enough for gasification (Gigler *et al.*, 2004). Artificial drying can be expensive but is also more effective. In practice, artificial drying is often integrated with the gasification plant to ensure a feedstock of constant moisture content. Waste heat from the engine/turbine can be used to dry the feedstock. Without drying the feedstock to a low moisture content gasification becomes difficult and inefficient.

2.1.4.2. Calorific value

The calorific value (CV) of a material is an expression of the energy content, or heat value, released when burnt in air. More specifically it is defined as the amount of thermal energy (enthalpy) released from the complete combustion of unit mass of fuel under standard conditions (Slesser, 1988). The CV is usually measured in terms of the energy content per unit mass, or volume; hence MJ/kg for solids, MJ/l for liquids, or MJ/Nm^3 for gases. The CV of a fuel can be expressed in two forms, the gross CV (GCV), or higher heating value (HHV) and the net CV (NCV), or lower heating value (LHV) (Slesser, 1988). The HHV is the total energy content released when the fuel is burnt in air, including the latent heat contained in the water vapour and therefore represents the maximum amount of energy potentially recoverable from a given biomass source (McKendry, 2002b). The LHV is calculated by deducting the latent heat of condensing water from the gross value (Slesser, 1988). As biomass has higher hydrogen content than fossil fuels, the difference between the GCV and NCV is higher, thus making moisture content more of an issue with biomass.

2.1.4.3. Elemental composition

The elemental composition of the fuel is important with respect to the CV and the emission levels in almost all applications. Elemental analysis of a fuel, presented as Carbon (C), Nitrogen (N), Hydrogen (H), Oxygen (O) and Sulphur (S) often together with the ash content, is termed the ultimate analysis of a fuel (ECN, 2009). Some examples of different biomass sources elemental compositions (including ultimate and proximate analysis) are included in Appendix B.

The production of nitrogen and sulphur compounds is generally small in biomass gasification because of the low nitrogen and sulphur content in biomass (Knoef, 2005). Exceptions may include manures, sludges, peat and other similar biomass, but these are not regarded as clean biomass feedstocks for gasification (IEE, 2007).

2.1.4.4. Volatile matter content

Volatile matter content, along with fixed carbon, provides a measure of how easily the biomass can be ignited and subsequently gasified, or oxidised (McKendry, 2002b). Tars and heavy hydrocarbons are released during the pyrolysis stage of the gasification process; hence the gasifier must be designed to destruct these (Knoef, 2005).

2.1.4.5. Other fuel related contaminants (e.g. metals)

The alkali metal content of biomass i.e. Na, K, Mg, P and Ca, is especially important for any thermochemical conversion processes (Bridgwater, 1995). A sticky liquid is produced when alkali metals react with silica present in the ash, which can lead to blockages of airways in furnaces and boiler plant. Producer gas (or wood gas) impurities such as tar, particulates, nitrogen compounds, sulphur compounds, and alkali compounds can cause problems in gasification, such as tars sticking to internal surfaces, particulates causing blocking and corrosion caused by alkali content (Gallagher, 2002). The use of wood gas in internal combustion engines therefore requires significant gas cleaning.

2.1.4.6. Bulk density and morphology

The bulk density refers to the weight of material per unit of volume and differs for various types of biomass. Together with the CV, it determines the energy density of the biomass feedstock, i.e. the potential energy available per unit volume of the feedstock (Biomass Energy Centre, 2010). Biomass of low bulk density is expensive and difficult to handle, transport and store.

2.1.4.7. Ash content and ash composition

Ash is the inorganic or mineral content of the biomass, which remains after complete combustion (Knoef, 2005). The amount of ash in different type of feedstocks varies widely, 0.1% for wood up to 15% for some agricultural products (ECN, 2009) and influences the design and efficiency of conversion processes. Ash composition can affect the performance, potential pollutants and subsequent method of ash disposal.

2.1.4.8. Cellulose/lignin ratio

All plants are made up of lignin and cellulose; they are large, complex molecules. Plants are built of cells, which have a cell wall made of cellulose and lignin (known as lignocellulose). Woody plants have a higher content of lignin. Without lignin, trees wouldn’t be able to stand up. The proportions of cellulose and lignin in biomass are important only in biochemical conversion processes, as lignin is very difficult to break down (McKendry, 2002b). This is much less important in thermochemical conversion.

2.2 BIOMASS CONVERSION TECHNOLOGIES

2.2.1 Introduction

Biomass can be converted into several useful forms of energy using different processes. Figure 2-2 portrays a number of different biomass (to bioenergy) conversion pathways. Various factors affect the choice of conversion process, these can include: the type, quantity and characteristics of biomass feedstock (see sections 2.1.3 and 2.1.4), the desired form of the energy, i.e. end-use requirements (see section 2.3), environmental standards, economic conditions, and project specific factors. In most situations it is the form in which the energy is required and the feedstocks which are available that determine the process route.

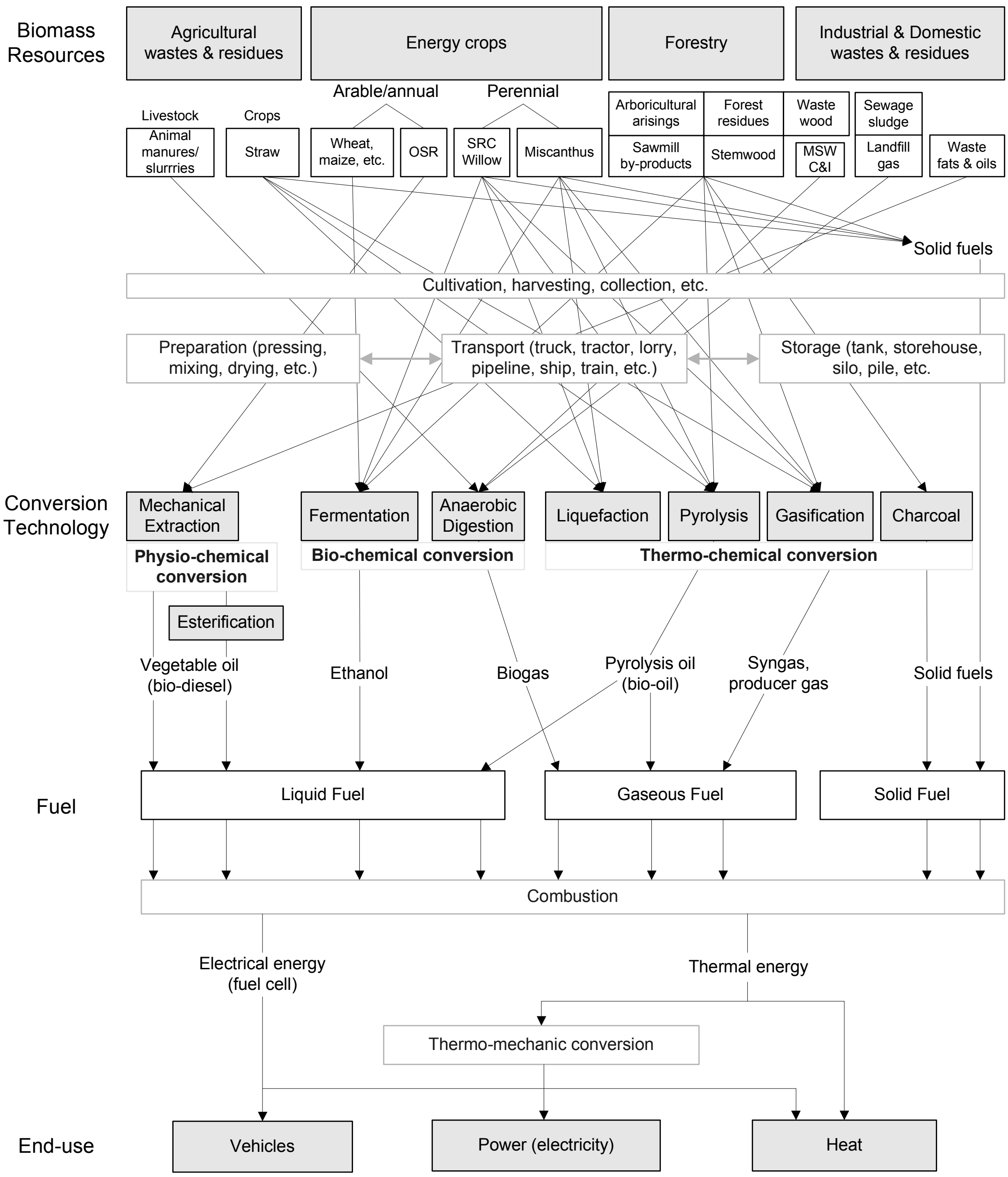


Figure 2-2: Schematic representation of biomass conversion pathways (adapted from FAO, 2004; Hammond *et al.*, 2008a; McKendry, 2002b)

Bioenergy is the term used to describe energy derived from biomass feedstocks. A number of stages (such as harvesting, drying, storage, transportation, etc.) are required to convert biomass into a useful energy source. Conversion of biomass to energy is undertaken using three main process technologies: thermo-chemical, bio-chemical, and physio-chemical. Within thermo-chemical conversion the four main process options are combustion, pyrolysis, gasification and liquefaction (McKendry, 2002b). Bio-chemical conversion encompasses two main process options: anaerobic digestion (production of biogas, a mixture of mainly methane and carbon dioxide) and fermentation (production of ethanol) (FAO, 2004). Physio-chemical conversion consists principally of extraction (with esterification) where oilseeds are crushed to extract oil (see section 2.2.4). This thesis is principally concerned with heat and power generation; however a brief overview of energy conversion options is presented.

2.2.2 Thermo-chemical conversion

Thermo-chemical conversion encompasses all conversion processes of biomass based on thermal energy. The main processes, the intermediate energy carriers and the final energy products resulting from thermo-chemical conversion are illustrated in the flowchart displayed in Figure 2-3.

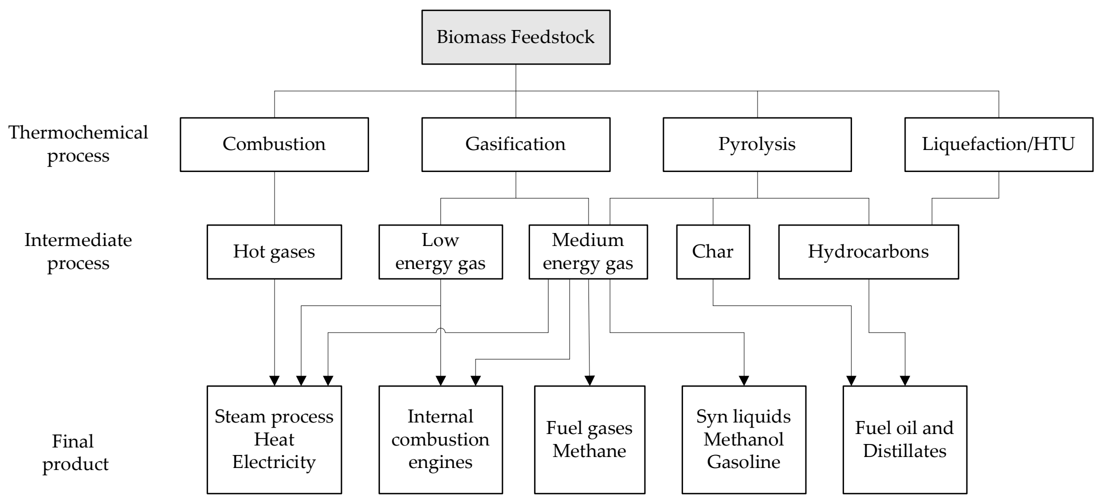


Figure 2-3: Main processes, intermediate energy carriers and final energy products from the thermo-chemical conversion of biomass (source: McKendry, 2002b)

2.2.2.1. Combustion

Combustion is the burning of biomass in air. It is used over a wide range of outputs to convert the chemical energy stored in biomass into heat, mechanical power, or electricity (see Figure 2-2). A variety of process equipment items can be used for combustion, e.g. fireplaces, stoves, boilers, gas turbines, etc. (Ecofys, 2005). During the combustion of biomass hot gases at temperatures around 800-1,000°C are produced (McKendry, 2002b). Whilst it is possible to burn any type of biomass, in practice combustion is only efficient if the moisture content (m.c.) of biomass is less than 50% otherwise most of the combustive energy is entrained in evaporated water within the flue gases (Deublein & Steinhauser, 2008). Biomass can be pre-dried to reduce the moisture but this requires energy, hence high m.c. biomass is better suited to biological conversion processes (see section 2.2.3).

Combustion plant sizes range from very small scale (e.g. domestic heating) typically in the range 15-50kW to large industrial scale plants in the range 100-3,000 MW (Ecofys, 2005). Recently in the UK the co-combustion of biomass in coal-fired power plants (known as co-firing) has become increasingly popular (Woods *et al.*, 2006). It was the introduction of the Renewables Obligation that provided the main stimulus for the development of co-firing (Ofgem, 2009). Biomass combustion for electricity has been commercially viable for a number of years, with many biomass fired plants in operation worldwide (Evans *et al.*, 2010). However, it is heat that is perhaps the most common and well known use provided through combustion (see section 2.3.1).

2.2.2.2. Gasification

Gasification is the conversion of biomass into a new energy carrier (in the form of a combustible gas mixture) by the partial oxidation of biomass at high temperatures, typically in the range 800–900°C (Ecofys, 2005). An oxygen-containing gasification medium such as air, oxygen or steam is applied to the heated biomass in a gasification reactor (Knoef, 2005). The organic substances are broken down into combustible compounds and the residual carbon undergoes partial combustion into carbon monoxide (Ecofys, 2005). Producer gas (also known as syngas) is produced which contains carbon monoxide, carbon dioxide, hydrogen, methane, trace amounts of higher hydrocarbons and ethane, water, nitrogen (if air is used as the oxidizing agent) and various contaminants such as small char particles, ash, tars and oils (Bridgwater, 1995). The low calorific value (CV) gas produced through air gasification (about 4–6MJ/Nm^3) can be burnt directly or used as a fuel for gas engines and gas turbines (McKendry, 2002c).

The production of producer gas from biomass allows the production of methanol and hydrogen, each of which may have a future as fuels for transportation (Hammond *et al.*, 2008a). Either oxygen-blown or hydrogen-indirect gasification processes are favoured in the production of methanol, because of the higher value CV gas (typically 9–11MJ/Nm^3) (McKendry, 2002c). Further investigation of these fuels is beyond the scope of this thesis as they are less suited to CHP and can be expensive to produce. Gasification with air is the most widely used technology since this avoids the costs and hazards of oxygen production and usage associated with oxygen gasification, and the complexity and cost of multiple reactors in steam gasification when two reactors are required (Bridgwater, 1995).

Figure 2-2 portrays that a diverse range of biomass feedstocks can be utilised in biomass gasification. Additionally gasification can be applied to derive a range of potential energy end-uses. Indeed biomass gasification is considered one of the most promising routes for combined heat and power (CHP) because of the potential for higher efficiency cycles (Knoef, 2005). Gas engines or combined gas- and steam- turbine cycles can be utilised where previously the fuel was limited by use in Rankine cycles (steam turbine) which typically have a lower electrical efficiency (IEE, 2007). Therefore it has been identified that biomass gasification (incorporating CHP) offers a very promising conversion technology. Consequently biomass gasification has been used as a case study in this thesis to investigate the potential life cycle environmental impacts, hence more information on this application is provided in section 0.

2.2.2.3. Pyrolysis

Pyrolysis is the conversion of biomass to liquid (termed bio-oil or bio-crude), solid and gaseous fractions, by heating the biomass in the absence of air to around 500°C; it is thermal decomposition occurring in the absence of oxygen (Bridgwater, 2004; IEA, 2007). Pyrolysis is always also the first step in combustion and gasification processes where it is followed by total or partial oxidation of the primary products (McKendry, 2002b). Lower process temperature and longer vapour residence times favour the production of charcoal (IEA, 2007). High temperature and longer residence time increase the biomass conversion to gas and moderate temperature and short vapour residence time are optimum for producing liquids (McKendry, 2002b). The product distribution obtained from different modes of pyrolysis process are summarised in Table 2-1.

In a pyrolysis process the char and volatiles remain largely unchanged; the energy in the biomass is thus transferred to the heating value of the volatiles and char removed from the reactor (Bridgwater *et al.*, 1999). These can be burned separately in turbines, engines or boilers to generate power. In some cases, the volatiles can be condensed to give a liquid that can be used as a fuel.

Table 2-1: Typical product yields (dry wood basis) obtained by different modes of pyrolysis of wood (source: IEA, 2007)

Mode	Operating Conditions	Liquid	Char (% weight)	Gas
Fast pyrolysis	~500°C, short hot vapour residence time ~ 1s	75	12	13
Intermediate	~500°C, hot vapour residence time ~10-30s	50	25	25
Slow – Torrefication	~290°C, solids residence time ~ 30 mins	-	82 (solid)	18
Slow – Carbonisation	~400°C, long vapour residence time hrs -> days	30	35	35
Gasification	~800°C	5	10	85

2.2.2.4. Liquefaction

Liquefaction is the conversion of biomass into a stable liquid hydrocarbon using low temperatures and high hydrogen pressures (FAO, 2004). The reactors and fuel-feeding systems required for liquefaction are more complex and more expensive than pyrolysis processes; consequently the interest in liquefaction is low (McKendry, 2002b). Another process that produces bio-oils is hydro thermal upgrading (HTU) which converts biomass in a wet environment at high pressure to partly oxygenated hydrocarbons (McKendry, 2002b). Liquefaction and HTU do not show good potential in the South West due to the expense and complexities, so will not be discussed further in this thesis.

2.2.3 Bio-chemical conversion

Bio-chemical (or biological) conversion processes include both anaerobic digestion (AD) and fermentation. AD and fermentation are natural processes which have been harnessed and used by man for thousands of years (Andersons, 2010). The science of both technologies is well understood and has been adapted to several feedstocks, environments, and purposes globally (Deublein & Steinhauser, 2008; FAO, 2004).

2.2.3.1. Anaerobic Digestion (AD)

AD is the conversion of organic material directly to a gas, known as biogas, which is a mixture of mainly methane and carbon dioxide with small quantities of other gases such as hydrogen sulphide (Deublein & Steinhauser, 2008). Organic non lingo-cellulosic (non-woody) material, the feedstock (also known as substrate), is converted by micro-organisms in the absence of oxygen (Andersons, 2010). This conversion process produces stable and commercially useful compounds and is similar to composting except that composting is aerobic (involving oxygen) in its breakdown of organic matter (Andersons, 2010). The biomass is converted by bacteria in an anaerobic environment, producing a gas with an energy content of about 20–40% of the LHV of the feedstock (McKendry, 2002b). AD is a commercially proven technology and is widely used for treating high moisture content organic wastes, i.e. 80–90% m.c. (Ecofys, 2005)

AD feedstock can be organic wastes and residues (such as animal manures or slurry) or energy crops (such as maize silage) grown specifically for feeding the AD plant. Anaerobic digesters produce conditions that encourage the natural breakdown of organic matter by bacteria in the absence of air. The two main products from an AD plant are:

- Biogas (also referred to as bio-methane). This is a mixture of about 60% methane, 40% carbon dioxide and traces of other 'contaminant' gasses (Deublein & Steinhauser, 2008). This is then combusted to generate electricity, heat or used as a road fuel.
- Soil conditioner. This is an inert and sterile wet product with valuable plant nutrients and organic humus. It can be separated into 'liquor' and fibre for application to land or secondary processing (Andersons, 2010).

Hence AD produces biogas which can be used directly in a gas engine or gas turbine but also provides a useful organic fertiliser as a by-product. It is therefore an extremely promising technology for the South West given total land used for farming and the amount of organic waste available in the region (Mezzullo, 2010).

2.2.3.2. Fermentation

Fermentation is used commercially on a large scale in various countries to produce ethanol from sugar crops (e.g. sugar cane, sugar beet) and starch crops (e.g. maize, wheat) (FAO, 2004). The biomass is ground down and the starch converted by enzymes to sugars, with yeast then converting the sugars to cellular energy and thereby producing ethanol (McKendry, 2002b). Purification of ethanol by distillation is an energy-intensive step which can result in relatively low net energy balances (Larson, 2006). Solid residues produced from the fermentation process can be used as cattle-feed and in the case of sugar cane, the bagasse can be used as a fuel for boilers or for subsequent gasification (McKendry, 2002b).

Perhaps the best known example of fermentation for fuel is the production of ethanol from sugar cane in Brazil (Worldwatch Institute, 2007). Sugar cane stalks contain sufficiently high amounts of sugar that the plant is currently the lowest cost source of producing ethanol (Enagri, 2010). Maize (also known as corn) is the second largest source of biofuel feedstock today, primarily because of its dominance in the US for ethanol production (Worldwatch Institute, 2007). Producing ethanol from grain starches is more land intensive than sugar cane, because the crops have lower fuel yields per hectare. The main sources of feedstock for fermentation in the UK are wheat and sugar beet. Both of these crops are grown for food purposes and there are not surpluses available sufficient for energy use; hence fermentation is not anticipated to be used for bioenergy production on a wide scale in the South West. It is therefore expected that producing bio-ethanol from wheat, sugar beets and other annual crops will not become common in the UK, with production limited to the primary cultivation areas in the east of England (ADAS, 2008).

2.2.4 Physio-chemical conversion

Physio-chemical conversion, also referred to as mechanical extraction, is a mechanical (physical) conversion process used to produce oil from the seeds of various biomass crops, such as oilseed rape (OSR) and linseed (FAO, 2004). This process provides a liquid fuel which can undergo a further stage, known as esterification, which turns the oil to fatty acid methyl ester, more widely known as bio-diesel (FAO, 2004). The process produces not only oil but also a residual solid or 'cake', which is suitable for animal fodder (McKendry, 2002b). This technology is used on a wide scale in Europe using vegetable oils from crops, primarily OSR, but waste fats and oils are also used. The main use of bio-diesel is as a liquid transport fuel; most commonly blended with diesel derived from petroleum (RFA, 2011). Physio-chemical conversion is not considered further within this thesis.

2.3 END-USES

There are three fundamental forms of energy which are commonly utilised in modern lifestyles: electricity, heat, and mechanical energy. Conversion of biomass to bioenergy results in a fuel which can be more easily converted into these useful fundamental forms of energy (see Figure 2-2). However raw biomass can also be used in some processes. Electricity generation (and CHP) can be implemented through methods of combusting solid biomass, or burning other forms of bioenergy such as biogas or liquid biofuels. Heat energy can also be supplied through bioenergy from the combustion of biomass. Liquid biofuels such as bio-ethanol, bio-diesel and biogas can be used in the transport industry.

2.3.1 Heat

Useful heat is generated in combustion systems which can range from small-scale, e.g. fireplaces to heat living spaces, to large-scale, e.g. district heating networks. Solid fuels are the dominant fuel used in stationary biomass systems which exist solely to generate heat. Wood as a raw material or residue is the primary biomass source for heat, both in the UK and globally (IEA, 2009). Heat can also be generated using biomass derived liquid and gaseous fuels but these are less commonly used than solid biomass fuels. Solid organic fuels are not flammable themselves under ambient conditions. Therefore in order to combust, a highly complex chain of thermochemical conversion processes needs to take place (Ecofys, 2005):

1. Heating – warming of the fuel (<100°C)
2. Drying of the fuel (100°C – 150°C)
3. Pyrolytic decomposition of the wood components (150°C – 230°C)
4. Gasification of the water-free fuel (230°C – 500°C)
5. Gasification of the solid carbon (500°C – 700°C)
6. Oxidation of the combustible gases (700°C – 1400°C)

2.3.2 Electricity

There are several options available for producing electricity from biomass. Biogenic gases are the most commonly utilised for stationary power generation applications (Deublein & Steinhauser, 2008). In the UK landfill gases and sewage sludge (via AD) are used to produce electricity (DECC, 2009a). Biogas produced from AD by recycling organic residues is an increasingly popular renewable electricity source (see section 2.2.3.1). Solid fuels can also be used to generate electricity; this usually employs a steam process to power turbines. Solid fuels are also often used in co-firing to generate electricity (see section 2.2.2.1). Liquid fuels are generally not used for biomass electricity but bio-diesel does have the potential to be a substitute for diesel generators.

The main driver in recent years for electricity produced from biomass has been the Renewables Obligation (Ofgem, 2009).

Producer (or syngas) from gasification is a biomass gaseous fuel which can be applied to electricity, but there are very few examples in the UK. In other parts of the world, particularly in Europe, there are several successful biomass gasification plants producing electricity (see for example (Knoef, 2005). Perhaps the primary benefit of biomass gasification, compared to direct combustion, is that extracted gasses can be used in a variety of power plant configurations.

The generation of power (electricity) from bioenergy can also make use of the capabilities of heat and power generation. Systems that generate mechanical power in combustion engines or turbines are coupled to electricity generators; these convert the mechanical energy into electrical energy with relatively low losses (Ecofys, 2005). Large amounts of heat are produced in electricity generation (approximately one-third power to two-thirds heat), much of which can be made useful via combined heat and power (CHP) (Deublein & Steinhauser, 2008). Due to its energy efficiency advantages, CHP has good potential for use in the UK and has therefore been chosen as part of the case studies in this thesis. Further background to CHP is provided in section 2.7.

2.3.3 Mechanical Energy

Mechanical energy is utilised principally in the transport industry, and is usually generated via heat engines. The main application for bioenergy is the use of liquid fuels (known as biofuels) with bio-ethanol and bio-diesel being the most common. In this process, the biofuel is ignited in an internal or external combustion engine; the expansion of the fuel/air mixture caused by combustion is then converted to mechanical power via crankshafts / turbine blades and gears (Ecofys, 2005). Heat generated in this process is dissipated via a cooling system.

Alternative biofuels which can be used in engines to produce mechanical energy include Fischer–Tropsch processed diesel, methanol, dimethyl ether (DME), and hydrogen (all via gasification), and bio-oil (from pyrolysis) (Hammond *et al.*, 2008a). Gaseous fuels, such as biogas, can also be utilised in engines, see for example (NSCA, 2006). These biofuels are beyond the scope of this thesis so are not further discussed.

2.4 BIOENERGY SYSTEMS

Bioenergy systems consist of several aspects to covert biomass into a useful energy end-use (as outlined above in sections 2.1 to 2.3). The exact stages required in a bioenergy system depend on a number of factors such as the biomass type, form and location and the desired end-use. The diversity of feedstocks and potential end-uses means that no two bioenergy systems will be identical. Some of the factors which can vary include:

- Land on which biomass resources are cultivated (soil, water, air quality, etc.);
- Weather patterns where biomass is grown (rainfall, sunlight, temperature, etc.);
- Cultivation and harvesting methods (crop management, fertilisers, irrigation, etc.);
- Quality of the biomass produced (yield, m.c., composition, CV, size, etc.)
- Pre-treatment required (pressing, drying, mixing, chopping, etc.)
- Transportation method and distances (tractor, lorry, ship, long distances, etc.)
- Storage (in-field, at farm, at plant, etc.)
- Biomass conversion technology (gasification, digestion, fermentation, etc.)

It is therefore apparent that when assessing bioenergy systems the boundaries must be defined and the parameters clearly stated. These considerations have also affected the scope of the research undertaken in this thesis. The diversity of biomass conversion pathways meant that a choice was made as to the specific biomass resources, conversion technologies and end-use which were chosen to assess. 'Bioenergy' is too broad to assess as a whole and as such individual case studies were chosen. Each pathway requires different resources, uses different processes, produces varying energy outputs and therefore has varied potential environmental impacts.

Evidence from the literature reveals that much work has been undertaken on the comparison of different bioenergy pathways of biofuels for transport (see for example, (Concawe, 2007; Larson, 2006; von Blottnitz & Curran, 2007). There appears to be less work comparing the potential environmental impacts of power generation systems, as noted by Larson (2006). Indeed this was also found by Thornley *et al.* (2009a) who completed an integrated assessment of bioelectricity options. There are several individual life cycle studies of biomass electricity and heat production (see for example, Elsayed *et al.*, 2003; Heller *et al.*, 2004; Keoleian & Volk, 2005), but most work completed has not gone beyond energy and carbon assessments. Hence it has been identified that there is a research need for full life cycle assessments (LCAs) of bioenergy electricity and heat systems, which assess a range of environmental impacts and not just energy and carbon.

Having undertaken a literature review, studied UK bioenergy development (see Chapter 4), and completed a resource assessment (see Chapter 5) it was decided to use perennial energy crops for the first case study. Miscanthus and Willow were chosen as they are both currently supported in England by the Energy Crops Scheme and have had the widest uptake of perennial energy crops in the UK (Natural England, 2009a). Both crops have a wide variety of potential end-uses (see Figure 2-2), but require high amounts of land to cultivate particularly when compared to waste streams. Another important reason is that growing perennial energy crops represents a different farming style and land use when compared to more traditional annual arable crops. Consequently it was identified that there was a need to better understand the potential environmental implications of a wider uptake of perennial energy crops.

Given that several previous studies have assessed the energy and carbon implications of these two crops (see for example, Bullard & Metcalfe, 2001; Matthews, 2001; Elsayed *et al.*, 2003), it is essential that this study goes beyond this by applying the full LCA methodology (ISO, 2006a) to assess a range of potential environmental impacts. Other studies found in the literature tend to assess one or two impacts or use literature review and not LCA methodology. For example, Rowe *et al.* (2009) completed a review of previous studies into the environmental impacts of perennial energy crops. Smeets *et al.* (2009) assessed the primary energy use and GHG balances of Miscanthus, but also soil erosion, biodiversity and water use through literature review. One study which did use LCA methodology followed the previous ISO (1997) standards and results were weighted (Monti *et al.*, 2009). Detailed inventory data and actual impact assessment results were not included in the Monti *et al.* (2009) journal, therefore its actual findings and assumptions are difficult to interpret. Hence there is a clear research need for a transparent and detailed LCA of perennial energy crops.

Biomass gasification was chosen for the second case study as it offers a range of potential benefits, as previously discussed (IEE, 2007; Knoef, 2005; McKendry, 2002c). Despite this array of potential advantages biomass gasification has low utilisation at present in the UK in comparison to mainland Europe (E4Tech, 2009). Consequently the potential impacts of this conversion technology are not well known in the UK. Therefore it has been identified that an LCA study of a biomass gasification plant construction and operation will add to the knowledge base.

Previous LCA studies of biomass gasification were limited to two studies found in the literature. Firstly, a detailed LCA of a large scale biomass gasification combined cycle (BGCC) plant produced some detailed results, but was completed before ISO (1997) standards were introduced (Mann & Spath, 1997). A second LCA of BGCC was completed which followed ISO (1997) standards and used Eco-Indicator 95 for the impact assessment, which is now over 15 years old (Carpentieri *et al*., 2005). Both of these systems were large scale and not considered appropriate in the UK given the amount of feedstock required. Also whilst they both represent valuable studies this technology is different to the one assessed in this thesis, as is the scale of the plant. Another important difference is that current ISO (2006) standards are followed in the present study along with up to date impact assessment methods and a detailed inventory provided.

Some further review of the results of these previous LCA and energy/carbon studies is included in Chapters 9 & 10. This is to compare the findings with the present study after the results have been presented.

2.5 PERENNIAL ENERGY CROPS

The ideal energy crop has efficient solar energy conversion resulting in high yields, needs low agrochemical inputs, has a low water requirement and has low moisture levels at harvest (Venturi & Venturi, 2003). While it is difficult to find a crop that meets all these criteria, perennial grasses, such as Miscanthus, and short rotation coppice (SRC), such as Willow (hereafter known as SRC Willow), are particularly promising (Rowe *et al*., 2009). Plants with perennial growth habits have the advantages of low establishment costs (when averaged across the rotation) and less annual operations are therefore required.

Miscanthus and SRC Willow have been chosen for examination in the LCA study presented in Chapter 6, therefore some background information is presented here. These two crops are already grown over 15,000 hectares in the UK to provide electricity and heat (Natural England, 2010). Government policies aim to encourage up to 350,000 hectares of these perennial energy crops by 2020 (DEFRA, 2007a). However, concerns have been raised about the likely effects on farm land biodiversity, water resources, familiar landscapes, as well as the pressures on land used for growing food crops (RFA, 2008). Another important aspect is the agronomic practices, which vary with intensity of production. Increasing the intensity of cultivation (i.e. the frequency of tillage, quantity of fertiliser, use of irrigation) can increases yields, but also increases GHG emissions and can challenge the goal of a sustainable production. In any case, it is clear that, to be accepted, perennial energy crops must fall within the parameters of sustainable agriculture.

2.5.1 Miscanthus

Miscanthus (*miscanthus giganteus*) species are woody, perennial, rhizomatous grasses originating from Asia, which have the potential for very high rates of growth (DEFRA, 2007b). The adaptability of Miscanthus to different environments and its high yielding potential (C4-plant), makes it suitable for establishment and distribution under a wide range of European climates (Lewandowski *et al*., 2000). Miscanthus is planted in spring and once planted can remain in the ground for at least fifteen to twenty years (Jones & Walsh, 2001). First year growth is not sufficient to be economically worth harvesting, however the crop can reach heights, from the second growing season onwards, of 2.5–3.5m in a single year, which is harvested annually between February and May (Smeets *et al*., 2009).

Miscanthus spreads naturally by means of rhizomes which can be split and the pieces re-planted to produce new plants. The leaves start to dry during autumn, as the nutrients are translocated back to the rhizomes by the end of the growing season (Jones & Walsh, 2001). Fertiliser requirements of the crop are very low due to good nutrient-use efficiency of the crop and autumn leaf fall as well as the plant's ability to recycle nutrients into the rhizomes at the end of the growing season (DEFRA, 2007b). Weed control in the critical establishment year of the crop is important; however, once the crop is well established from the second or third year onwards, weed growth can be adequately suppressed by the leaf litter layer produced on the soil surface and by the closure of the crop's canopy (Bullard & Metcalfe, 2001).

2.5.2 Willow

Willow grown as short rotation coppice (SRC Willow) consists of densely planted, high-yielding varieties of Willow, harvested on a two- to five-year cycle, although commonly every three years (Keoleian & Volk, 2005). SRC Willow is a woody, perennial crop, the rootstock or stools remaining in the ground after harvest with new shoots emerging the following spring. SRC Willow yields will vary according to the location of the site. Soil type, water availability, general husbandry, and pest and weed control affect yield.

High-density plantations of around 15,000 stools per hectare are usually established from Willow cuttings (Goglio & Owende, 2009). Plantation establishment involves winter–spring planting of cuttings followed by a first-year growth as single stems. In the following winter, these single stems are cut back to ground level to encourage the production of multiple stems, resulting in the development of dense plantations of multi-stemmed stools (DEFRA, 2002). Harvested material is chipped and dried for use in several end-use applications. The establishment of SRC plantations has more in common with agricultural or horticultural crops than forestry (Matthews, 2001).

Figure 2-4: Miscanthus being grown at Wadswick Farm, Corsham, Wiltshire and Holt Farms, Blagdon, Somerset

Figure 2-5: SRC Willow being grown at Long Ashton Research Centre, Bristol, Somerset

2.6 BIOMASS GASIFICATION

2.6.1 Gasification process

Gasification is a process in which a solid material containing carbon, such as coal or biomass, is converted into a gaseous fuel by heating in a gasification medium such as air, oxygen or steam (Knoef, 2005). It is a thermochemical process, meaning that the feedstock is heated to high temperatures, producing gases which undergo chemical reactions to form a synthesised gas. Gasification converts the intrinsic chemical energy of the carbon in the biomass into a combustible gas in two stages, whereas in combustion oxidation is substantially complete in one process (McKendry, 2002c). The gas produced can be standardised in its quality and is more versatile to use than the original biomass, e.g. it can be used to fuel gas engines and gas turbines.

The gasification process follows several steps (see Figure 2-6), which are explained below (Bridgwater, 1995; Hofbauer, 2007; Knoef, 2005, McKendry, 2002c):

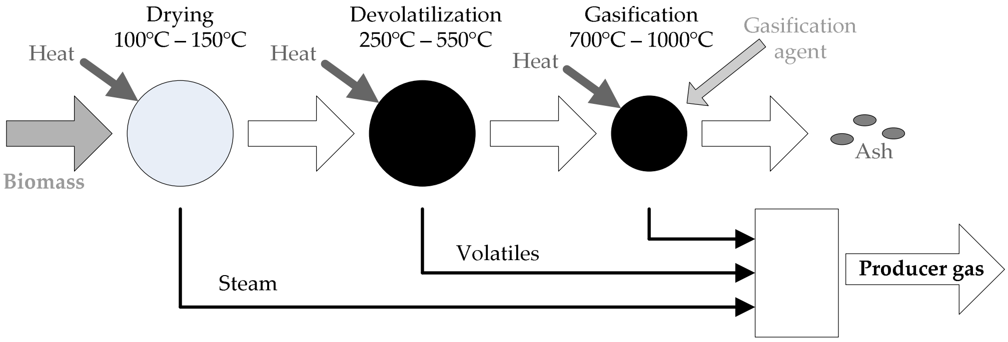


Figure 2-6: Processes during gasification of a single particle (source: Hofbauer, 2007)

- Drying to evaporate moisture
- Pyrolysis vaporises the volatile component of the feedstock (devolatilisation) as it is heated. The volatile vapours are mainly hydrogen, carbon monoxide, carbon dioxide, methane, hydrocarbon gases, tar, and water vapour. Solid char and ash are also produced.
- Gasification further breaks down the pyrolysis products with the provision of additional heat:

  - Some of the tars and hydrocarbons in the vapours are thermally cracked to give smaller molecules, with higher temperatures resulting in fewer remaining tars and hydrocarbons
  - Steam gasification - this reaction converts the char into gas through various reactions with carbon dioxide and steam to produce carbon monoxide and hydrogen
  - Higher temperatures favour hydrogen and carbon monoxide production, and higher pressures favour hydrogen and carbon dioxide production over carbon monoxide
- The heat needed for all the above reactions to occur is usually provided by the partial combustion of a portion of the feedstock in the reactor with a controlled amount of air, oxygen, or oxygen enriched air. Heat can also be provided from external sources such as natural gas.
- There are then further reactions of the gases formed, with the reversible water-gas shift reaction changing the concentrations of carbon monoxide, steam, carbon dioxide and hydrogen within the gasifier. The result of the gasification process is a mixture of gases

All steps such as drying, devolatilization, and also gasification of the remaining char are endothermic (heat-absorbing) and, therefore, heat has to be supplied to keep them running (Hofbauer, 2007).

2.6.2 Basic Chemistry

The reactions taking place in the gasifier can be summarised as indicated below (Knoef, 2005; McKendry, 2002c):

Partial oxidation	$C + \frac{1}{2} O_2 \leftrightarrow CO$	dH = – 268 MJ/kg mole	(eq. 2.3)
Complete oxidation	$C + O_2 \leftrightarrow CO_2$	dH = – 406 MJ/kg mole	(eq. 2.4)
Water gas reaction	$C + H_2O \leftrightarrow CO + H_2$	dH = + 118 MJ/kg mole	(eq. 2.5)

The greatest energy release is derived from the complete oxidation of carbon to carbon dioxide i.e. combustion (see eq. 2.4), while the partial oxidation of carbon to carbon monoxide accounts for only about 65% of the energy released during complete oxidation (McKendry, 2002c). This is shown by the heats of reaction for the three processes, where – denotes exothermic reactions and + denotes endothermic reactions. Unlike combustion that produces only a hot gas product, carbon monoxide, hydrogen and steam can undergo further reactions during gasification as follows (Knoef, 2005; McKendry, 2002c):

Water gas shift reaction	$CO + H_2O \leftrightarrow CO_2 H_2$	dH = – 42 MJ/kg mole	(eq. 2.6)
Methane formation	$CO + 3H_2 \leftrightarrow CH_4 + H_2O$	dH = – 88 MJ/kg mole	(eq. 2.7)

The arrows indicate that the reactions are in equilibrium and can proceed in either direction, depending on the temperature, pressure and concentration of the reacting species (McKendry, 2002c). From these chemical equations it follows that the producer gas consists of a mixture of carbon monoxide, carbon dioxide, methane, hydrogen and water vapour.

2.6.3 Gasification technologies

There are several different generic types of gasification technology that have been demonstrated or developed for conversion of biomass feedstocks. It is beyond the scope of this thesis to provide background to all of the various different gasification technologies. There are several excellent publications which review and discuss these (see for example, Bridwater, 1995; E4Tech, 2009; IEE, 2007; Knoef, 2005; McKendry 2002c). The factors which affect the choice of technology and some further information on entrained flow gasification is included in Appendix B.

2.7 COMBINED HEAT AND POWER (CHP)

Combined heat and power (CHP) (also known as cogeneration) is the use of a heat engine or other energy conversion technology (e.g. fuel cells) to simultaneously generate both electricity and useful heat (Carbon Trust, 2010). In accordance with the 2nd law of thermodynamics all power plants must emit a certain amount of heat during electricity generation (Oland, 2004); this can be into the natural environment through cooling towers, flue gas, or by other means. In conventional ways of generating electricity vast amounts of heat are simply wasted due to insufficient local demand. In contrast CHP captures some of the by-product heat for space heating purposes, or as hot water for district heating.

The CHP plant in the biomass gasification case study comprises a lean burn gas engine that drives an electrical generator combined with equipment to recover the energy that would normally be lost in the exhaust gases to provide heating and hot water (see Figure 2-7). This makes CHP much more energy efficient than electricity from remote power stations and cuts CO_2 emissions (Cogenco, 2009). This case study offers one way of producing CHP, but several other CHP technologies do exist (see for example, Oland, 2004).

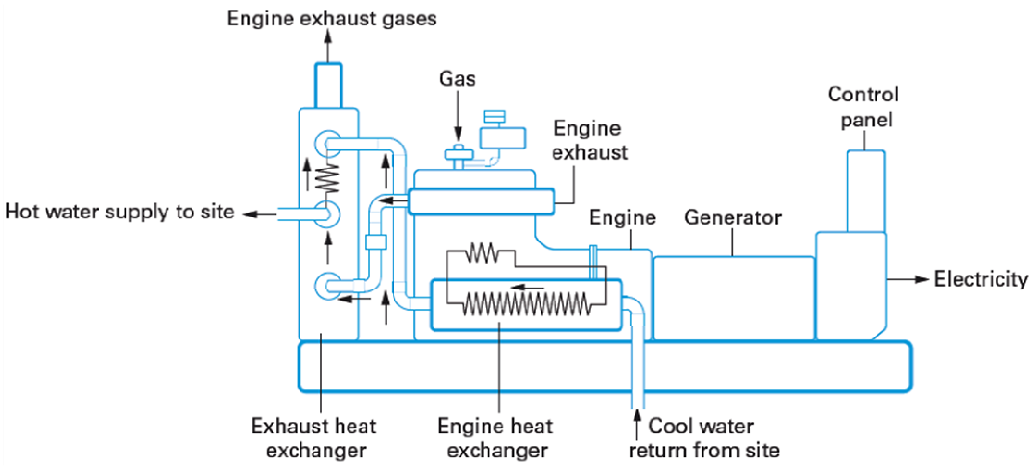


Figure 2-7: Overview of combined heat and power plant (source: Carbon Trust, 2010)

2.7.1 CHP engines

CHP is very common in biomass gasification and AD (biogas) plants. In parallel to the generation of electrical current, a relatively high percentage of heat is developed in CHP systems. The amount of heat generated depends on the energy conversion technology used. A variety of conversion technologies exist for CHP, which differ widely (Deublein & Steinhauser, 2008). Some further data on engine characteristics is provided in Appendix B.

2.7.2 Cogenco CHP unit

The CHP unit used in the case study presented in Chapters 7 to 9 is produced by Cogenco. This comprises of a four-stroke gas engine, generator, electrical output, hot water output, heat exchanger, and various monitoring and control equipment (see Figure 2-8).

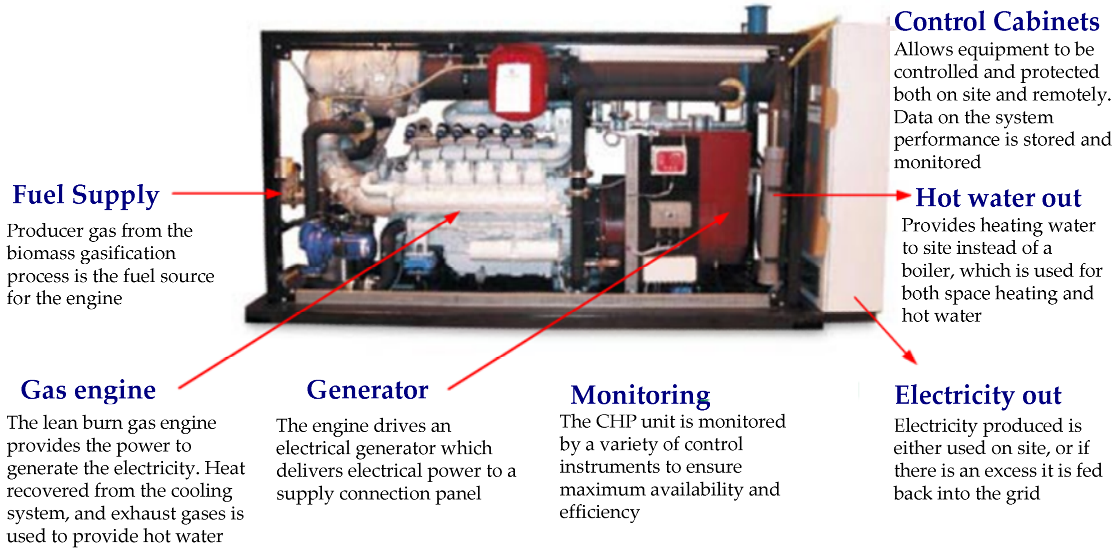


Figure 2-8:Overview of Cogenco CHP Unit (source: Cogenco, 2009)

2.8 SUMMARY

This chapter has provided an overview of bioenergy systems and describes the main terminology used throughout this thesis. It highlights that there are many ways in which biomass can be converted into useful energy, and it becomes apparent that bioenergy production is very diverse. Each bioenergy pathway may perform differently in terms of delivered energy produced and potential environmental impacts or benefits. There may also be varying amounts of the different biomass sources available which affects the utility of different bioenergy pathways. Information is therefore required on the different aspects of bioenergy systems.

Potential aspects of different bioenergy systems were discussed in section 2.4, along with an explanation as to why the case studies presented were chosen for this thesis. A discussion of previous LCA studies performed on the chosen studies was included to highlight relevant research gaps. Additional information was then provided for perennial energy crops (section 2.5), biomass gasification (section 0), and combined heat and power (CHP) (section 2.7), as these were chosen for the LCA and net energy analysis case studies presented in chapters 6 to 10. It is beyond the scope of this thesis to assess the energy outputs and potential environmental impacts of several bioenergy pathways due to the vast amount of data required in a LCA.

Another important finding from this chapter is due to the number of biomass sources which are available it is valuable to quantify this resource for a given region. Hence in Chapter 5 a biomass resource assessment is completed for the South West, which helped to identify Miscanthus and Willow as being potentially vital in future bioenergy production. From this resource assessment it was also identified that biomass gasification CHP has the potential to utilise several of the available feedstocks.

Although the majority of this chapter is based on literature review, it serves a useful purpose in providing relevant information with which to understand biomass and bioenergy. It was not proposed to present a comprehensive overview of 'bioenergy' per se, but instead provide sufficient background knowledge relevant to this thesis. Furthermore it is intended that the reader will have a better understanding of why the case studies presented later in this thesis were chosen (i.e. gaps in research were identified through a critical review of previous LCA studies).

CHAPTER 3. METHODOLOGIES

In undertaking this research a variety of different methodologies have been applied to assess the original research questions. To understand why the methodologies used in this research were selected, it is helpful to revisit the research aims and objectives in Chapter 1. The methodologies chosen were selected based on the most appropriate way to address these research questions. This chapter therefore outlines the methodologies implemented in this thesis in the following four sections:

- UK bioenergy development (section 3.1);
- Biomass resource assessment (section 3.2);
- Life cycle assessment (section 3.3);
- Net energy analysis (section 3.4).

This is a useful and necessary starting point to understand the background and theory behind each methodology. Each of the methodologies presented are applied to the case studies in the subsequent chapters. Table 3-1 summarises the research objectives from Chapter 1 and shows which of the methodologies are used to address each objective, and where they are applied in this thesis.

Table 3-1: Summary of research objectives and which methodologies applied

	Objective	Comments	Methodology (section)				Where applied in thesis
			3.1	3.2	3.3.	3.4	
1	Outline bioenergy systems terminology and describe why case studies selected	Literature review					Chapter 2
2	Define methodologies used for interdisciplinary assessment of bioenergy	This chapter					Chapter 3
3	Assess barriers to and drivers for UK bioenergy development		✓				Chapter 4
4	Quantify biomass resource available in the South West of England			✓			Chapter 5
5	Assess potential environmental impacts of perennial energy crop growth				✓	✓	Chapters 6 & 9
6	Assess potential environmental impacts of biomass gasification				✓	✓	Chapters 7 to 9
7	Incorporate results from objectives 5 & 6 to assess different bioenergy systems and compare with other energy systems				✓	✓	Chapter 10

In this chapter the main elements to each of the four methodologies are outlined. It should be made clear that for the UK bioenergy development study (in section 3.1) and the biomass resource assessment (in section 3.2) further details of the methodology applied are included in Chapters 4 and 5 respectively. This is because some supporting information is required within the chapters. In contrast the life cycle assessment (in section 3.3) and net energy analysis (in section 3.4) methodologies have more detailed information contained within the present chapter as these case studies (presented in Chapters 6 to 10) go straight into the analysis. Hence it can be seen that sections 3.1 and 3.2 are shorter and less detailed than sections 3.3 and 3.4.

3.1 UK BIOENERGY DEVELOPMENT METHODOLOGY

One of the main aims of this research was to understand the current UK bioenergy market and assess how this may develop over the next decade and beyond. To address this aim an initial literature review was completed to identify the current bioenergy situation in the UK. From this it became apparent that there were a number of factors which affected the success of bioenergy project implementation. To investigate these factors a study was completed in collaboration with another PhD research student (Mezzullo, W.G.). The methodology applied in this study is outlined here, with further background, full results and analysis presented in Chapter 4. The limitations to the study are discussed in Chapter 11.

3.1.1 Literature and Case Study Review

An initial literature and bioenergy project case study review was undertaken to assess the various factors which may affect UK bioenergy development. It was found that there were several bioenergy projects which, for various reasons, were unsuccessful. There were also numerous examples of successful bioenergy projects. These reviews helped to identify the reasons for success or failure of bioenergy projects. The literature review also established the current UK and EU bioenergy policies which are driving development.

3.1.2 Identify Barriers to and Drivers for UK Bioenergy Development

From the literature and bioenergy project case study review a number of so-called 'barriers' to UK bioenergy development were identified. In the UK, for example, the main barriers to bioenergy projects are understood to arise from financial problems during operation of plant; increased transport around bioenergy plants; local planning approval location of bioenergy plant; mistrust between local community, developers and agencies; credibility of developer; environmental impacts and technical problems. In contrast there are also various incentives, or 'drivers' for UK bioenergy development. These vary from Government policy incentives through to environmental motivations.

3.1.3 Identify Key Stakeholders

The root causes for unsuccessful bioenergy projects can originate from any or multiple stages of the project's development chain. The supply chain, considered a critical part of the success of bioenergy development (Gill *et al.*, 2005), is ultimately created between the demand for bioenergy and the supply of the energy source. The four main areas that can affect a bioenergy supply chain were considered to be: farmer or supplier of feedstock, plant developer or owner, primary end-users and government/policy stakeholders. Further description of these stakeholders and the supply chain is presented in Chapter 4.

3.1.4 Propose Barriers and Drivers for each Stakeholder Group

Once the four main stakeholder groups were identified, a number of barriers and drivers for each group were proposed. As each stakeholder group has different characteristics and motivations it was considered important to propose the barriers and drivers separately for each group, hence different surveys were used for each group. An advantage of this was to understand the differences and similarities in motivations and attitudes of each group.

3.1.5 Stakeholder Survey

An online survey was then carried out for each of the four stakeholder groups. Each questionnaire was different based on the barriers and drivers identified in the literature. The online questionnaires postulated the list of proposed barriers and drivers to the development, use and support of bioenergy. Respondents were asked to assess the importance of each of the barriers and drivers on a 4-point scale [critical importance to unimportant]. They could also indicate if they were 'undecided', and also had the opportunity to add other barriers or drivers. The study focused on more overarching aspects of development as opposed to specific (or plant-dependent) issues. It is accepted that the chosen methodology was just one approach to analysing UK bioenergy development. For practical reasons (i.e. time and resource constraints), an online survey was most appropriate.

3.1.6 Results Analysis

Once the surveys were completed, the respondents submitted their assessments; these were stored in an online database. Data were collated into the four stakeholder categories, and analysed to determine the most important barriers and drivers to UK bioenergy development.

3.1.7 Discussion and Interpretation of Findings

The final stage was to discuss and interpret the results of the stakeholder surveys. Several useful and interesting findings were found which had implications for how the UK bioenergy market may develop. There were also important conclusions on the key factors for the success of individual bioenergy projects and how this may influence UK bioenergy policy.

3.1.8 Summary

The key stages of the UK bioenergy development study presented in Chapter 4 are summarised in Figure 3-1:

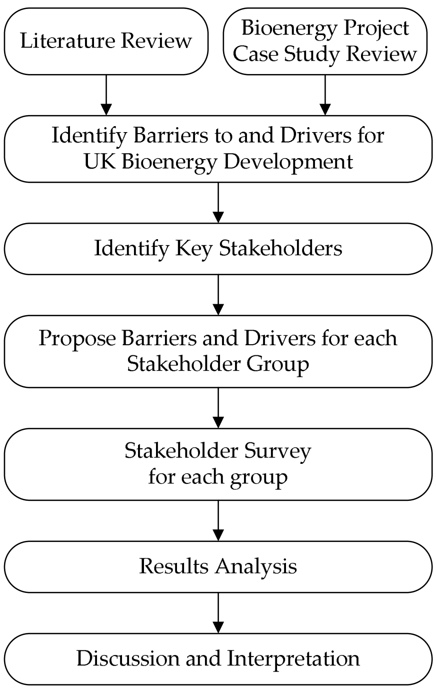


Figure 3-1: Key stages of the UK bioenergy development study

3.2 BIOMASS RESOURCE ASSESSMENT METHODOLOGY

A variety of different biomass resources are available in the South West of England, the UK and abroad. Therefore the starting point for the resource assessment was to identify and define the biomass resources to be included in the study. It was decided to focus on those resources which were available in the South West, therefore biomass resources from other parts of the UK and abroad were not included. The general methodology adopted for this resource assessment followed 7 key stages which are outlined in the following sections. The findings of the resource assessment and more specific detail on each biomass feedstock are presented in Chapter 5.

3.2.1 Biomass classification

There are different approaches to biomass classification systems used in resource assessments. For example, in a previous resource assessment of the South West, biomass was divided into wood and non-wood biomass sources (Hammond *et al.*, 2008b) as proposed by (Rosillo-Calle *et al.*, 2007). In this study it was decided to use a different classification system because in the South West wood is not the dominant resource; agriculture is the most important land use, waste streams are extremely varied and energy crops consist of wood, grasses and other plants. Essentially the type of biomass classification system employed in a resource assessment does not matter, just as long as it is clearly defined. The different categories used in the study were:

- Agricultural wastes and residues
    - Animal manures
    - Straw
- Energy crops
    - Perennial energy crops – Miscanthus and short rotation coppice (SRC)
    - Conventional crops – annual crops: cereals, oilseed rape, sugar beet
- Forestry
    - Forestry residues
    - Stemwood
    - Sawmill co-products
    - Arboricultural arisings
- Industrial and domestic wastes and residues
    - Waste wood
    - Sewage sludge
    - Municipal solid waste (MSW)
    - Commercial and industrial waste streams
    - Landfill gas

Further description of each of these categories is given in the relevant section in Chapter 5.

3.2.2 Review of existing biomass resource assessments

There has already been a number of biomass resource assessments completed on a global, European, national and regional level. From these studies there is a broad agreement that a few factors affect the contribution that bioenergy can make to primary energy supply. These include: the availability of land, biomass productivity, competition for land, the biomass itself, and waste materials derived from biomass (Berndes *et al.*, 2003). A background literature review for each feedstock was therefore an important stage of this study. Previous resource assessments were reviewed to obtain existing resource datasets, methodologies and the assumptions adopted. This background review also helped to identify competing uses of biomass and possible constraints on biomass supply.

3.2.3 Data collection

Data collection methods varied for each feedstock depending on a number of different factors. These included: national datasets maintained; quality and detail of datasets; transparency of information obtained; assumptions used; knowledge of competing sectors; constraints on supply; accuracy of previous studies, etc. Due to the different data available for each feedstock, a full description is given in the relevant section in Chapter 5.

3.2.4 Analysis of current and future biomass resource

Having collected data for each feedstock type, the next stage was to analyse the current available resource. An estimate of the future potential resource was also made.

3.2.5 Apply constraints

The range of potential feedstocks highlights that biomass is a complex and diverse resource. The availability of these materials tends to be intertwined with activity in other major economic sectors: agriculture, forestry, food processing, paper and pulp, building materials etc. (Faaij, 2006). Hence supply-chains for biomass feedstocks are correspondingly complex. This complexity is accentuated by the diversity in the composition of the biomass. Its chemical structure, moisture content, etc. is highly variable, and therefore different types of biomass may have restricted applications to a particular conversion technology.

Other factors which may affect biomass availability may include how accessible it is. For example, some animal wastes are very dispersed and therefore difficult and presently uneconomic to collect. Social constraints may include such factors as perceptions of food crop displacement or the visual aspect of tall energy crop growth. Economic factors are also critical as biomass may have a higher value in an alternative use, or low density biomass can be expensive to transport. Contaminated feedstocks such as wood waste could be considered an environmental constraint. All of the above examples give an indication of some of the possible restrictions on the availability of biomass. Therefore applying constraints was considered an important stage in this resource assessment.

3.2.6 Quantify current resource and define resource equation

To quantify the current resource, all of the data was gathered, the existing biomass resource was analysed and the constraints were applied. This produced an estimate for each feedstock as to the total amount of biomass which could be realistically available in the South West. It was also considered useful to define a resource equation for each feedstock. This took into account such factors as the resource, availability, yields, existing uses, etc. The resource equation varied for each feedstock depending on which factors affected the available biomass resource.

3.2.7 Identify end-use and future possible resource

The final stage of the resource assessment was to assess the potential end-use of each biomass feedstock type, e.g. manures used in an anaerobic digestion system or waste wood used for gasification. This stage gives an indication of the potential energy which could be generated using the available biomass resource. Finally, the future possible resource was assessed to give an indication of how the availability of each biomass feedstock may change over time.

3.2.8 Summary

The critical stages in the biomass resource assessment presented in Chapter 5 can be summarised as follows:

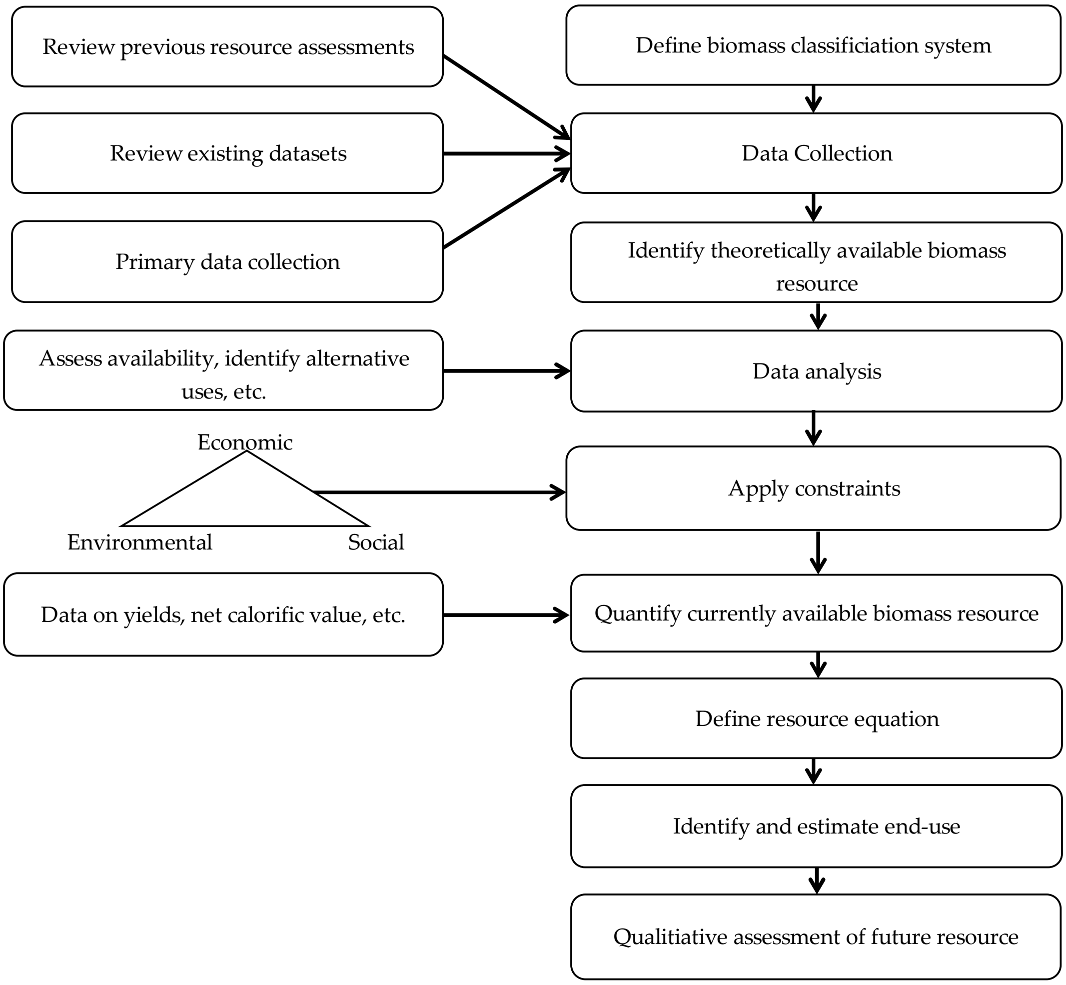


Figure 3-2: Critical stages of the biomass resource assessment methodology

3.3 LIFE CYCLE ASSESSMENT METHODOLOGY

3.3.1 Background

Life Cycle Assessment (LCA) is an environmental management tool that assesses the environmental impact of a product or system over its entire life, from ‘cradle to grave’. It is widely recognised that to evaluate the environmental consequences of a product or activity, the impact which results from each stage of its life cycle must be considered (Hammond & Winnett, 2006). There is a broad agreement in the scientific community that LCA is one of the best methodologies for the evaluation of the environmental burdens associated with bioenergy production (Royal Society, 2008; von Blottnitz & Curran, 2007). By identifying energy and materials used as well as waste and emissions released to the environment, it also allows an identification of opportunities for environmental improvement (Cherubini *et al.*, 2009; Consoli *et al.*, 1993).

There are several definitions of LCA, but they all essentially follow the International Organization for Standardization (ISO) which defines LCA as the “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (ISO, 2006a).

3.3.2 LCA Methodology

There are four main stages in the LCA process shown in Figure 3-3 and described in the following sections below:

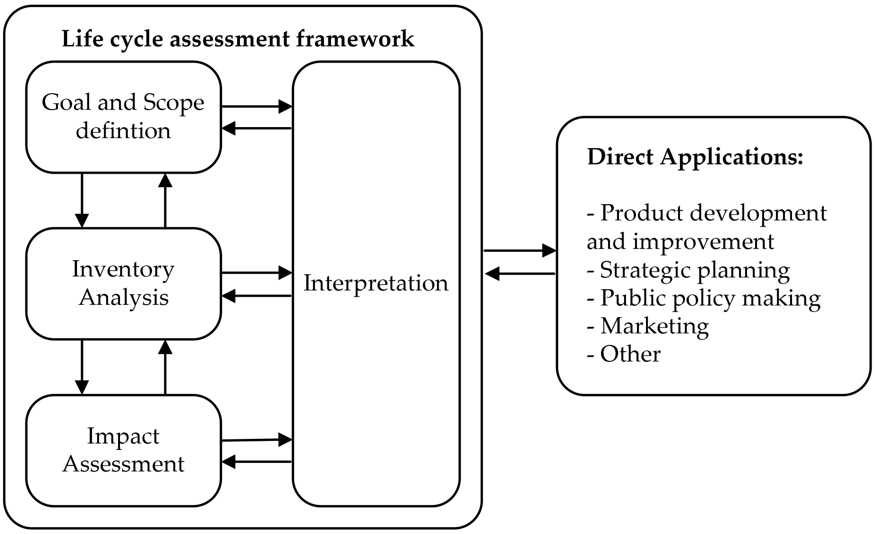


Figure 3-3: Main stages in LCA (source: ISO, 2006a; ISO, 2006b)

3.3.2.1. Goal and scope definition

The **goal and scope definition** of an LCA provides a description of the product system in terms of the system boundaries, purpose, and a functional unit. The goal of a LCA study specifies the intended application of subsequent results, the reasons for generating these results and the expected audience for these results. The scope of a LCA study establishes its coverage by defining the nature of the product under examination and by summarising the level of detail in which it is being examined (Curran, 2006).

The **functional unit** is the important basis that enables alternative goods, or services, to be compared and analysed. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related (ISO, 2006a). This reference is necessary to ensure comparability of LCA results. The functional unit is not usually just a quantity of material, LCA practitioners generally compare a quantity of a delivered product or service that the product provides. Comparability arises if the environmental burdens are attributed to a unit, for instance a relevant example for bioenergy production is to compare the production of 1kWh of electricity from a biomass energy pathway with 1kWh produced from the UK grid. This is explored in more detail in chapter 10.

LCA is conducted by defining product systems as models that describe the key elements of physical systems (ISO, 2006a). The **system boundary** defines the unit processes to be included in the system. In establishing the systems boundary, an imaginary line is drawn around the life cycle. Boundaries for a system in LCA should be set as broadly as possible. Processes involved in the extraction of raw materials and production of ancillary (intermediate) materials must be included in addition to accounting for the energy and material flows of the primary product. Ancillary materials are used indirectly in the manufacture of the final product, for example fertilisers used in the production of biomass. Disposal, by-products, and wastes are also included within the life cycle boundary. At a simple level, systems boundaries can be used to indicate whether the inventory analysis is part of a so-called "cradle-to-grave" or "cradle-to gate" LCA study (Curran, 2006).

When setting the system boundary, the main life cycle stages, unit processes and flows which are taken into consideration include the following (ISO, 2006a):

- acquisition of raw materials;
- inputs and outputs in the main manufacturing/processing sequence;
- distribution/transportation;
- production and use of fuels, electricity and heat;
- use and maintenance of products;
- disposal of process wastes and products;
- recovery of used products (including reuse, recycling and energy recovery);
- manufacture of ancillary materials;
- manufacture, maintenance and decommissioning of capital equipment;

At the goal and scope stage it is beneficial to create a flow diagram incorporating all of the possible impacts and effects from the study.

3.3.2.2. Inventory analysis

Inventory analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system, and generate the life cycle inventory (LCI). The process chain is the sequence of specific activities involved in the production, use, and final disposal of the product under consideration. Data for each unit process within the system boundary can be classified under major headings, including:

- energy inputs, raw material inputs, ancillary inputs, and other physical inputs;
- products, co-products and waste;
- emissions to air, discharges to water and soil; and
- other environmental aspects.

Data collection is the most demanding and time consuming task in performing an LCA. However, numerous databases exist which provide inventory data on various materials and processes. Data collection is therefore usually split into two main types:

- foreground (or primary) data
- background (or secondary) data

Foreground data refers to the specific data which is obtained directly from modelling a product system. This primary data is usually obtained via companies and through direct measurement or analysis. It is typically data that describes a particular product system. Background data is data for generic materials, energy, transport and waste management systems, which is generally data found in databases and literature. A combination of foreground and background data is required to produce the life cycle inventory (LCI).

3.3.2.3. Impact Assessment

Life Cycle Impact Assessment (LCIA) aims to describe, or indicate, the impacts of the environmental loads quantified in the inventory analysis. Impact assessment is where actual affects on the selected environmental burdens are assessed. The main purpose of LCIA is to convert inventory results into more environmentally appropriate information. LCIA therefore presents information on impacts on the environment, as opposed to just information on emissions and resource use. Another purpose, which is often overlooked, is to aggregate the information from the LCI into fewer parameters. The impact assessment phase is broken down into different elements as illustrated in Figure 3-4.

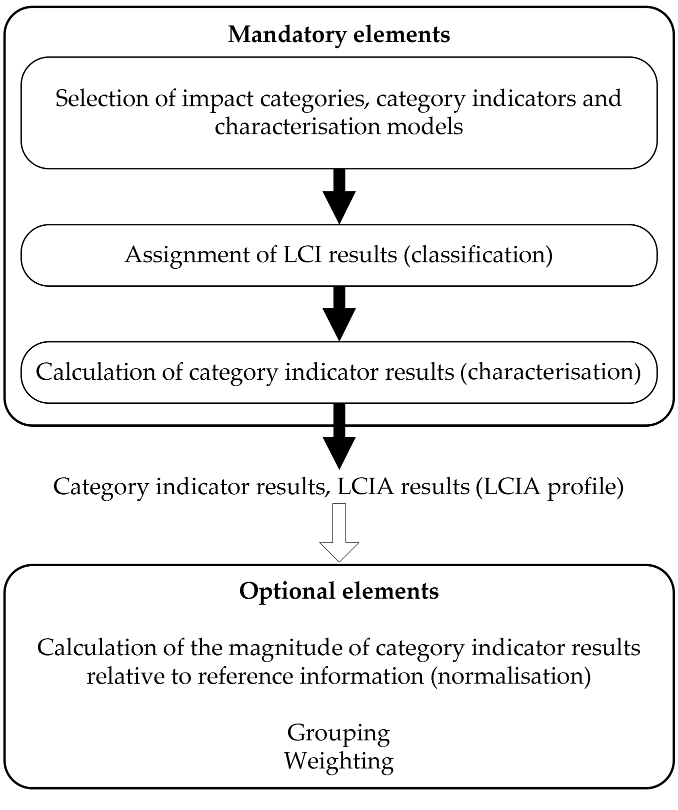


Figure 3-4: Elements of the LCIA Phase (source: ISO, 2006a)

Accordingly, every LCA must at least include classification and characterisation. If such procedures are not applied, then the study can only be referred to as a 'life cycle inventory'. The main elements completed in the LCA case studies presented in this thesis include:

- Classification – simply means aggregating the inventory data according to the type of environmental impact they contribute to.
- Characterisation – is where the relative contributions of the emissions and resource consumptions to each environmental impact are calculated.
- Normalisation – here results are made dimensionless to allow comparison of the relative importance of each impact category.

Valuation is a subjective process which assigns relative values or weights to impacts in order to facilitate comparisons. It is not used in this study as it is not recommended by ISO standards.

Classification is where the data from the inventory are assigned to environmental impact categories. For example, greenhouse gas (GHG) emissions, acidification, mineral resource depletion, etc. (N.B. inventory data can be assigned to more than one impact category).

Once the impact categories are defined and the LCI results are assigned to these impact categories, it is necessary to define **characterisation** factors. These factors reflect the relative contribution of an LCI result to the impact category indicator result. In each class there are numerous different types of emissions, all of which have different effects in terms of the given impact category, e.g. GHGs and their differing global warming potentials (GWPs). A characterisation step is therefore performed to enable these emissions to be directly compared and added together. In this step, a list is yielded of environmental impact categories for which a single number can be allocated.

Characterised data are very difficult to compare directly due to their very different units of measurement. For example, GHGs are measured in kg of CO_2eq., whereas Acidification is measured in kg of SO_2eq. To overcome the problem of comparing impact categories the normalisation step can be used. Using normalised results allows a comparison of the importance of each impact category.

Normalisation compares characterised data with some yard-stick, i.e. the impact category result is compared with a reference system. Normally this is the amount of emissions created by a country or a region, during a certain time. This number is often very large and so can be divided by the number of people in the country or region. This can be achieved using the notation of 'people emission equivalents', which can be defined for the present purposes as follows:

$$\text{European emissions per capita} = \frac{\text{Total European output in each emission category}}{\text{Population of Europe}} \qquad \text{(eq. 3.1)}$$

$$\therefore \text{ People emission equivalents} = \frac{\text{Emissions from the process studied}}{\text{European emissions per capita}} \qquad \text{(eq. 3.2)}$$

People emission equivalents can therefore be compared with the emissions from the product or system to determine its significance in comparison with all the other emissions. Emissions can also be compared with national limits. Data in this thesis have been normalised with respect to average European emissions. This allows a comparison of the importance of each category to be made without attributing subjective valuation.

The two main purposes of using the normalisation step are:

1. Impact categories that contribute only a very small amount compared to other impact categories can be left out of consideration, thus allowing focus on the significant impacts where improvements might be made.

2. The normalised results show the order of magnitude of the environmental problems generated by the products life cycle, compared to the total environmental loads in Europe.

3.3.2.4. Interpretation

Interpretation is the phase of LCA in which the findings from the inventory analysis and the impact assessment are considered together. This stage uses the information gathered in the study to identify and implement areas for potential improvement. According to ISO 14040, the interpretation phase should deliver results that are consistent with the defined goal and scope; results should be interpreted; conclusions should be reached; limitations should be explained; and recommendations provided (ISO, 2006b). The interpretation of LCIA results should also demonstrate that the results indicate potential environmental effects, and that they do not predict actual impacts on category endpoints.

Curran (2006) identifies three key steps to interpreting the results of the LCA:

1. Identification of the significant issues based on the LCI and LCIA.
2. Evaluation which considers completeness, sensitivity, and consistency checks.
3. Conclusions, recommendations, and reporting.

These 3 steps help provide a constructive systematic approach to interpreting the life cycle. Significant issues may include inventory parameters (e.g. energy use, emissions, waste, etc.); impact category indicators (e.g. health impacts, resource depletion, etc.); and essential contributions for life cycle stages (e.g. raw material extraction, processing, transportation, etc.). The evaluation step establishes the confidence in and reliability of the results of the LCA. It is here where the sensitivity analysis is performed which assesses the relative importance of the assumptions made in the study. Finally, conclusions are drawn and recommendations are made.

3.3.3 LCA Software

LCA is a very data intensive environmental management methodology utilising large amounts of data. This LCI data is generally then processed using an impact assessment methodology. Various commercially available software packages have been developed to process this data efficiently and effectively. It is important to choose the most appropriate package and understand the benefits and potential disadvantages of using software. For this research 9 LCA software options were reviewed (see Appendix C). The SimaPro package was used in the LCA case studies presented in this thesis.

3.3.3.1. SimaPro

SimaPro is a commercial LCA software tool that contains several inventory databases (see section 3.3.4) and several impact assessment methods (see section 3.3.5), which can be edited and expanded without limitation. It can compare and analyse complex products with complex life cycles. SimaPro contains a large database of some of the more commonly used materials, processes and products, and these can be amended, updated and added to as extra data become available. These inventories are often applicable to a range of LCA studies and sometimes take an average of the different manufacturing/extraction methods. Information contained in SimaPro can be displayed in tabular, graphical and flow chart form and can be exported into other formats such as Excel. This allows transportation of data and allows results to be presented in a suitable manner. SimaPro allows the LCA to comply with the ISO standards.

3.3.3.2. Advantages and disadvantages of using LCA software

The main attractions of using LCA software can be summarised as:

- Provides an organised framework within which to perform calculations, often of a very repetitive nature;
- Enables a considerable amount of data to be handled easily and quickly;
- Usually contains extensive databases for performing calculations;
- Allows different life cycle impact assessment methodologies to be used;
- Results can be presented in a structured and readily understandable way.

It is therefore clear that due to the large amount of data needed for a LCA, using software is very beneficial. Nonetheless, some caution is required as there are also some possible disadvantages of using software. McManus (2001) describes these as:

- The black box problem – Results can be generated very easily and quickly and users may think that the results are accurate and complete when they are not.
- Not understanding the process – Untrained people can easily produce "LCAs" without understanding the process, which could lead to inaccurate LCAs being produced.
- Data quality – Results can be obtained as soon as any data are put into a database, but this gives no assurance of its usefulness or accuracy.

3.3.4 Inventory Databases

Several LCI databases exist which are very useful in providing background data for LCA studies. The (background) data available in SimaPro are structured in a way which allows the user to view (for any given material or process) all material and energy inputs, products, co-products, wastes and emissions to air, water and soil. Further information is also provided on the data sources and data quality. This provides a very transparent, comprehensive set of data which is simple to use. This is important as care must been taken when using background data, as the user has not personally collected the data.

Ecoinvent is a comprehensive and peer-reviewed inventory dataset which has been used in the LCA studies performed in this thesis (Swiss Centre for Life Cycle Inventories, 2009). The key characteristics of the Ecoinvent database can be summarised as:

- Covers a very broad range of data;
- Consistent application of system boundaries and allocation;
- Well documented with extensive background reports available;
- Consistent specification of uncertainty data;
- Regular updates can be purchased from the Ecoinvent centre.

3.3.5 Impact Assessment Methodologies

A number of life cycle impact assessment methodologies (LCIAM) exist to process LCI data into more environmentally appropriate information. Figure 3-5 gives a general overview of the structure of a LCIAM. It shows that results are characterised to produce a number of impact category indicators.

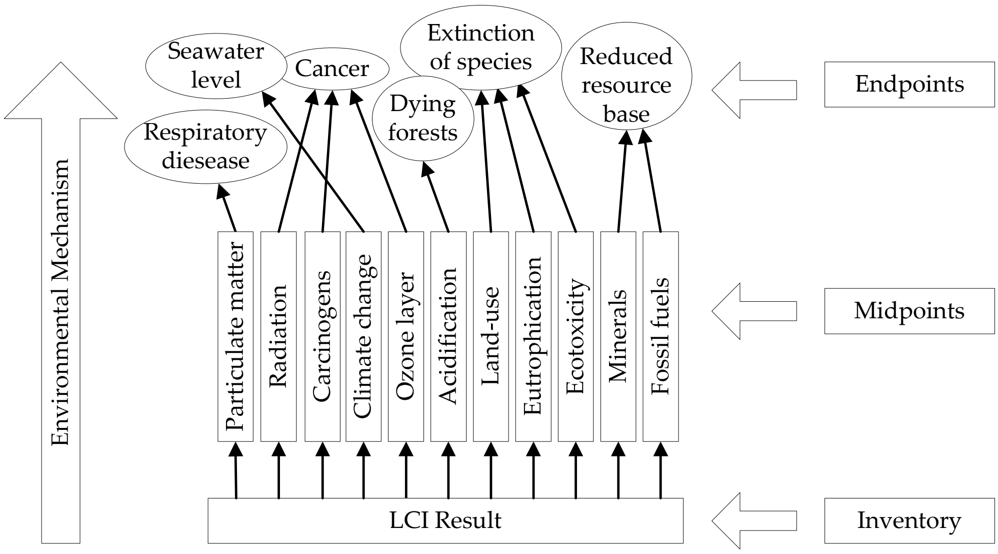


Figure 3-5: General overview of the structure of an impact assessment method (adapted from Pre Consultants, 2008)

When selecting which impact assessment methodology to use, it is important to consider which environmental issues are relevant. To help with the selection process is the definition of so-called "endpoints" (see Figure 3-5). Endpoints can be understood as issues of environmental concern, such as damage to human health, species extinction, resource depletion, etc. ISO 14044 requires a careful selection and definition of endpoints first, after that impact categories can be selected (ISO, 2006b). The ISO 14044 standard allows the use of impact category indicators that are somewhere between the inventory result (i.e. emission) and the endpoint (ISO, 2006b). Indicators which are selected between the inventory result and the endpoints are generally referred to as indicators at the "midpoint".

3.3.5.1. Review of Impact Assessment Methodologies available

A number of life cycle impact assessment methodologies (LCIAMs) are commercially available. Several factors affect the choice of which methodology to use in a LCA, the most important of which is the desired aggregation level of the results. This is effectively whether results are presented at the midpoint or endpoint level. Other essential considerations are the impact categories to be included, characterisation methods, geographical location, etc. Table 3-2 displays the summarised findings of the review undertaken to choose the most suitable published and peer-reviewed LCIAMs for this thesis. It demonstrates that some LCIAMs are more suitable than others. Further description of this review is included in Appendix C.

Table 3-2: Impact Assessment Methodologies reviewed for this study

LCIAM Name	Midpoint/ Endpoint	Advantages	Disadvantages	Background publication
CML 2001	midpoint	Commonly used in Europe; up to date characterisation factors	Does not include land use or particulate matter	Guinée et al., 2002
Cumulative Energy Demand (CED)	n/a	Best available LCIAM for net energy analysis	Does not assess other environmental impacts	Frischknecht et al., 2007
Cumulative Exergy Demand (CExD)	n/a	Useful for exergy analysis	Does not assess other environmental impacts	Frischknecht et al., 2007
Eco-indicator 99	endpoint	Comprehensive impact categories and characterisation factors	Noise and odour not included	Goedkoop et al., 2000
Ecological footprint	midpoint	detailed assessment of land use	Only considers land use	Frischknecht et al., 2007
Ecological scarcity	endpoint	Calculates "eco-factors" for several impact catergories	Largely based on Swiss data; includes subjective weighting	Brand et al., 1998
Ecosystem damage potential (EDP)	midpoint	Characterises land occupations & transformation	Only considers land use	Koellner & Scholz, 2007
EDIP 2003 – Environmental Design of Industrial Products	midpoint	Covers most of the emission-related and resource use impacts	Does not include land use or differentiate between fossil fuel and mineral resource depletion	Hauschild & Potting, 2004
EPS 2000 – Environmental priority strategies in product development	midpoint	Includes a number of impact categories	Some impacts calculated in a course manner; not up to date	Steen, 1999
IMPACT 2000+	midpoint & endpoint	Characterisation factors based on CML and Eco-indicator 99	Better to use other original LCIAMs as more up to date characterisation factors	Jolliet et al., 2003
IPCC 2001 (Climate Change)	midpoint	Detailed assessment of climate change	Only considers climate change	Frischknecht et al., 2007
ReCiPe	midpoint & endpoint	Comprehensive LCIAM with 18 impact categories and up to date characterisation factors	Water depletion and marine eutrophicaton not assessed at the endpoint	Goedkoop et al., 2009
TRACI - Tool for the Reduction & Assessment of Chemical & Other Environmental Impacts	midpoint	Similar categories to Eco-indicator 99	Characterisation factors are for USA; depletion characterisation models not implemented in SimaPro	Bare et al., 2002

This review found that CML (for midpoint) and Eco-Indicator 99 (for endpoint) were the most commonly used LCIAMs in European LCA studies. Alongside ReCiPe these had the most comprehensive characterisation factors. CML does not include land-use or particulate matter formation, which were both considered to be critical when assessing bioenergy systems, hence CML was excluded from consideration. ReCiPe is a relatively new impact assessment methodology which combines both CML and Eco-Indicator 99 and provides more up to date characterisation factors. Both ReCiPe and Eco-indicator 99 were selected for the case studies for reasons described in the next section.

3.3.6 Impact assessment approach adopted in case studies

ReCiPe was selected as the main LCIAM used for the case studies. Reasons for choosing ReCiPe included:

- It is the first LCIAM which presents results at both the midpoint and endpoint using a consistent approach;
- Impact categories were relevant and most appropriate – includes land use, fossil fuel depletion, mineral resource depletion, particulate matter formation;
- Provides very up to date characterisation factors and normalisation data;

- European characterisation factors and normalisation data – most relevant to this study, and generally more comprehensive than other regions;

A clear advantage of using ReCiPe is that results are presented at both the midpoint and the endpoint. The approach adopted was to assess results at the endpoint first to identify the issues of environmental concern, such as damage to human health, species extinction, resource depletion, etc. for each impact category. Characterised results were used to highlight the biggest contributions to each impact category and the normalised results used to identify the significant impact categories.

Since ReCiPe is a very new LCIAM it was considered useful to also assess results at the endpoint using Eco-Indicator 99 to compare findings and confirm the key issues. Using endpoint methodologies assesses the potential damages and is thus easier to understand and interpret by decision makers than midpoint (Pre Consultants, 2008). Eco-Indicator 99 is widely respected and commonly used throughout the LCA community, so provides a rigorous LCIAM to confirm the key issues alongside ReCiPe (endpoint).

Key issues were then further analysed using ReCiPe (midpoint) as these indicators are chosen closer to the inventory result and hence have a lower uncertainty. In summary, the main results and findings presented in this thesis use ReCiPe as the LCIAM, with Eco-Indicator 99 employed to verify the ReCiPe (endpoint) findings. Figure 3-6 displays the impact assessment approach adopted in the LCA case studies presented in this thesis.

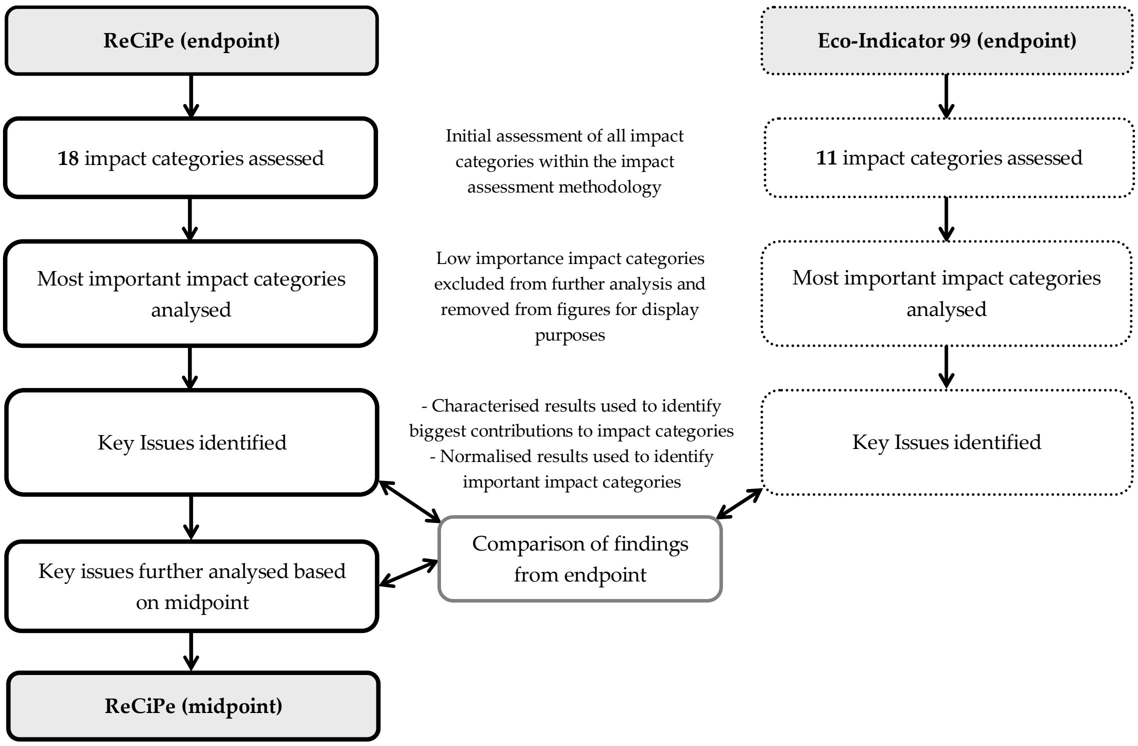


Figure 3-6: Impact assessment approach adopted in the LCA case studies

3.3.7 ReCiPe

ReCiPe comprises two sets of impact categories with associated sets of characterisation factors (Goedkoop *et al.*, 2009). Results at the midpoint use CML from the Handbook on LCA as the baseline method for characterisation (Guinée *et al.*, 2002); Eco-indicator 99 is used as the basis for endpoint characterisation (Goedkoop *et al.*, 2000). Although these are based on existing methods, the characterisation and normalisation factors have been updated. New research into environmental mechanisms and characterisation models, along with new impact categories have also been incorporated into ReCiPe. Figure 3-7 represents the ReCiPe methodology in a schematic way, showing the relationship between LCI parameters (left), midpoint indicators (middle) and endpoint indicators (right).

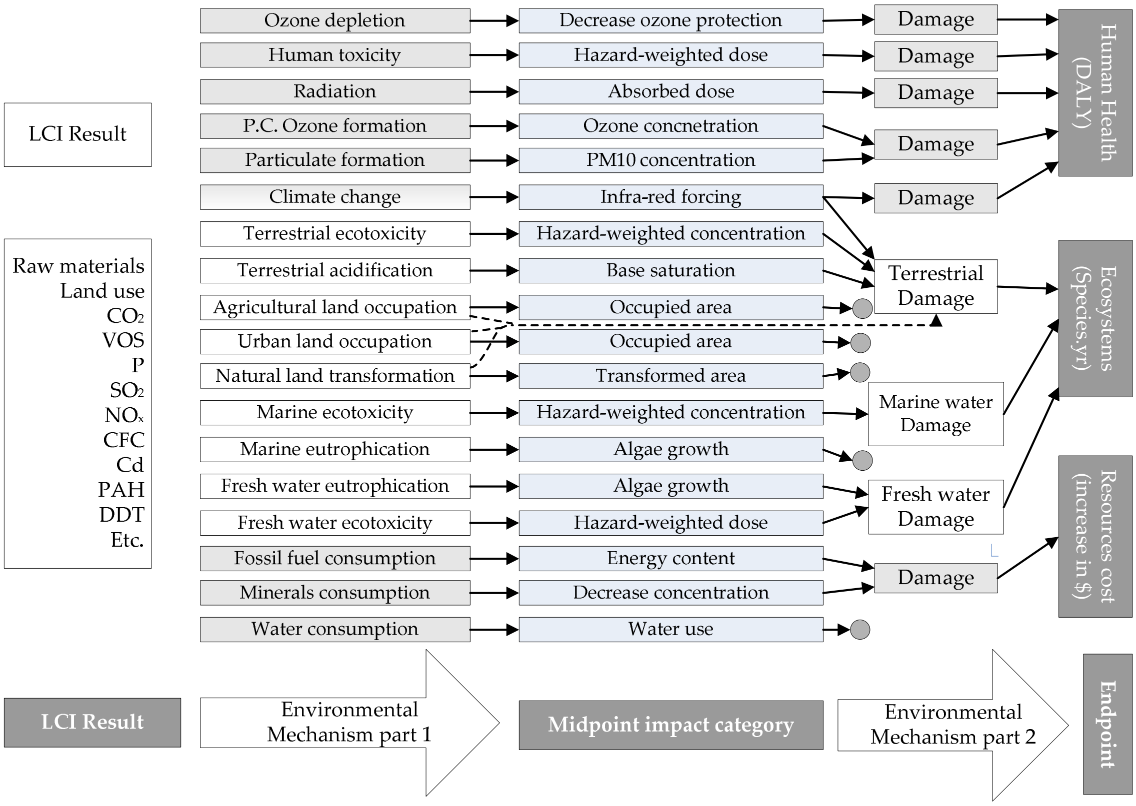


Figure 3-7: General representation of ReCiPe methodology (source: Goedkoop *et al.*, 2009)

Midpoint impact categories reflect issues of direct environmental relevance. The impact categories are names, but category indicators are measurable places in an impact pathway. Eighteen impact categories and indicators are addressed at the midpoint level as presented in Table 3-3. The calculation of the magnitudes of these category indicators requires characterisation factors, which in turn require characterisation models (see Table 3-4).

Impact categories at the endpoint correspond to areas of protection that form the basis of decisions in policy and sustainable development. For the environmental domain, these areas of protection are human health, ecosystem quality and resource availability. The man-made environment is not included in ReCiPe. Table 3-5 summarises the endpoint categories, indicators and characterisation factors.

Table 3-3: Overview of the midpoint categories and indicators in ReCiPe (source: Goedkoop *et al.*, 2009)

Impact category name (abbreviation)	Indicator name	Unit *
climate change (CC)	infra-red radiative forcing	$W \times yr/m^2$
ozone depletion (OD)	stratospheric ozone concentration	ppt†×yr
terrestrial acidification (TA)	base saturation	$yr \times m^2$
freshwater eutrophication (FE)	phosphorus concentration	$yr \times kg/m^3$
marine eutrophication (ME)	nitrogen concentration	$yr \times kg/m^3$
human toxicity (HT)	hazard-weighted dose	–
photochemical oxidant formation (POF)	Photochemical ozone concentration	kg
particulate matter formation (PMF)	PM10 intake	kg
terrestrial ecotoxicity (TET)	hazard-weighted concentration	$m^2 \times yr$
freshwater ecotoxicity (FET)	hazard-weighted concentration	$m^2 \times yr$
marine ecotoxicity (MET)	hazard-weighted concentration	$m^2 \times yr$
ionising radiation (IR)	absorbed dose	man×Sv
agricultural land occupation (ALO)	occupation	$m^2 \times yr$
urban land occupation (ULO)	occupation	$m^2 \times yr$
natural land transformation (NLT)	transformation	m^2
water depletion (WD)	amount of water	m^3
metal depletion (MD)	grade decrease	kg^{-1}
fossil depletion (FD)	upper heating value	MJ

* The unit of the indicator is the unit of the physical or chemical phenomenon modelled.

† The unit ppt refers to units of equivalent chlorine.

Table 3-4: Overview of the midpoint categories and characterisation factors in ReCiPe (source: Goedkoop *et al.*, 2009)

Impact category abbreviation	Unit *	Characterisation factor name
CC	kg (CO_2 to air)	global warming potential
OD	kg (CFC-11[5] to air)	ozone depletion potential
TA	kg (SO_2 to air)	terrestrial acidification potential
FE	kg (P to freshwater)	freshwater eutrophication potential
ME	kg (N to freshwater)	marine eutrophication potential
HT	kg (1,4-DCB to urban air)	human toxicity potential
POF	kg (NMVOC[6] to air)	photochemical oxidant formation potential
PMF	kg (PM_{10} to air)	particulate matter formation potential
TET	kg (1,4-DCB to industrial soil)	terrestrial ecotoxicity potential
FET	kg (1,4-DCB to freshwater)	freshwater ecotoxicity potential
MET	kg (1,4-DCB[7] to marine water)	marine ecotoxicity potential
IR	kg (U^{235} to air)	ionising radiation potential
ALO	$m^2 \times yr$ (agricultural land)	agricultural land occupation potential
ULO	$m^2 \times yr$ (urban land)	urban land occupation potential
NLT	m^2 (natural land)	natural land transformation potential
WD	m^3 (water)	water depletion potential
MD	kg (Fe)	metal depletion potential
FD	kg (oil†)	fossil depletion potential

* The unit of the impact category here is the unit of the indicator result.

† The precise reference extraction is "oil, crude, feedstock, 42 MJ per kg, in ground".

Table 3-5: Overview of the endpoint categories, indicators and characterisation factors

Impact category name	Indicator name	Unit
damage to human health	disability-adjusted loss of life years	yr
damage to ecosystem diversity	loss of species during a year	yr
damage to resource availability	increased cost	$

Damage models for most of the midpoint categories link these damage categories with the inventory and midpoint result. Table 3-5 showed that the endpoint damage categories relate to an area of protection. These three damage categories are briefly described here (Goedkoop *et al.*, 2009).

3.3.7.1. Damage to human health

LCAs commonly assess damage to human health using the concept of 'disability-adjusted lifeyears' (DALY). Hofstetter (1998) introduced the DALY-concept in LCA, which is based on the work carried out by Murray and Lopez (1996) for the World Health Organisation. The DALY of a disease is derived from human health statistics on life years both lost and lived disabled. The damage model is applied in four steps:

- Fate analysis, linking an emission (expressed in basic S.I. units) from the LCI to a temporary change in concentration.
- Exposure analysis, linking this temporary concentration to a dose.
- Effect analysis, linking the dose to a number of health effects, like the number and types of cancers.
- Damage analysis, links health effects to DALYs, using estimates of the number of Years Lived Disabled (YLD) and Years of Life Lost (YLL).

3.3.7.2. Damage to ecosystem diversity

Ecosystems are heterogeneous and very complex to monitor. Ecosystem quality can be described in terms of energy, matter and information flow. In the ReCiPe model the information flow at the species level is used. This means accepting the assumption that the diversity of species adequately represents the quality of ecosystems. This model gives the results as the potentially disappeared fraction of species (PDF) per unit area (m^2 or m^3) over a specified time period (yr).

3.3.7.3. Damage to resource availability

Resource depletion is modelled using the geological distribution of mineral and fossil resources and assesses how the use of these resources causes marginal changes in the efforts to extract future resources. The model is based on the marginal increase in costs due to the extraction of a resource. In terms of minerals, the effect of extraction is that the average grade of the ore declines, while for fossil resources, the effect is that not only conventional fossil fuels but also less conventional fuels need to be exploited, as the conventional fossil fuels cannot cope with the increasing demand. The marginal cost increase is the factor that represents the increase of the cost of a commodity r ($/kg), due to an extraction or yield (kg) of the resource r. The unit of the marginal cost increase is dollars per kilogramme squared ($\$/kg^2$).

3.3.8 Impact categories and environmental issues

A brief description of the impact categories and environmental issues found to be relevant to bioenergy systems is provided here. Goedkoop *et al.* (2009) provide full details of the characterisation models, environmental mechanisms and supporting literature.

Climate change

Climate change causes a number of environmental mechanisms that affect both the endpoint human health and ecosystem health. Climate change models are generally developed to assess the future environmental impact of different policy scenarios. In ReCiPe it is the marginal effect of adding a relatively small amount of CO_2 or other GHGs which is modelled (Goedkoop *et al.*, 2009).

Acidification

Atmospheric deposition of inorganic substances, such as sulfates, nitrates, and phosphates, cause a change in acidity in the soil. For almost all plant species there is a clearly defined optimum of acidity. A serious deviation from this optimum is harmful for that specific kind of species and is referred to as acidification. Consequently, changes in levels of acidity will cause shifts in species occurrence (Hayashi *et al.*, 2004). Major acidifying emissions are NO_x, NH_3, and SO_2.

Eutrophication

Aquatic eutrophication can be defined as nutrient enrichment of the aquatic environment. Eutrophication in inland waters as a result of human activities is one of the major factors that determine its ecological quality. The long-range character of nutrient enrichment, either through air or rivers, implies that both inland and marine waters are subject to this form of water pollution, although due to different sources and substances and with varying impacts (Goedkoop *et al.*, 2009).

Toxicity

Characterisation factors of human toxicity and ecotoxicity account for the environmental persistence (fate) and accumulation in the human food chain (exposure), and toxicity (effect) of a chemical. Fate and exposure factors can be calculated by means of 'evaluative' multimedia fate and exposure models, while effect factors can be derived from toxicity data on human beings and laboratory animals (Hertwich *et al.*, 1998; Huijbregts *et al.*, 2000).

Particulate matter formation

Fine particulate matter with a diameter of less than 10 μm (PM_{10}) represents a complex mixture of organic and inorganic substances. PM_{10} causes health problems as it reaches the upper part of the airways and lungs when inhaled. Secondary PM_{10} aerosols are formed in air from emissions of sulfur dioxide (SO_2), ammonia (NH_3), and nitrogen oxides (NO_x) among others (World Health Organization, 2003). Inhalation of different particulate sizes can cause different health problems.

Land use

The land use impact category reflects the damage to ecosystems due to the effects of occupation and transformation of land. Although there are many links between the way land is used and the loss of biodiversity, ReCiPe concentrates on the occupation of a certain area of land during a certain time, and the transformation of a certain area of land (Goedkoop *et al.*, 2009).

Water depletion

Water is a scarce resource in many parts of the world, but also a very abundant resource in other parts of the world. Extracting water in a dry area can cause very significant damages to ecosystems and human health, but so far no models are available to express the damage on the endpoint level. ReCiPe does include a midpoint indicator that simply expresses the total amount of water used (Goedkoop *et al.*, 2009).

Metal depletion

A mineral is in nature extracted from a deposit (that is extracted in a mine) and most deposits contain several minerals (Verhoef *et al.*, 2004). Eventually, the minerals or metals are the economic output of a mining operation and therefore also called commodities. In the description of the area of protection, the damage is defined as the additional costs society has to pay as a result of an extraction. This cost is calculated by multiplying the marginal cost increase of a resource with an amount that is extracted during a certain period (Goedkoop *et al.*, 2009).

Fossil fuel resource depletion

The term fossil fuel refers to a group of resources that contain hydrocarbons. The group ranges from volatile materials (like methane), to liquid petrol, to non-volatile materials (like coal). When conventional fossil fuel production is limited by scarcity, new, so called unconventional sources will be needed to ensure sufficient supply. Unconventional fossil resources are generally more energy intensive and more costly to produce, compared to conventional fuels. ReCiPe calculates the marginal cost to society of extracted these unconventional fossil resources (Goedkoop *et al.*, 2009).

3.4 NET ENERGY ANALYSIS METHODOLOGY

As the UK strives to achieve a low carbon society, a major focus is increasing the use of renewable energy technologies. In order to change a society's energy system various forms of investment are required and, as with money, energy is invested to ultimately provide or save energy (Allen, 2009). In the case of bioenergy technologies, the energy investment in the energy-supply process only makes sense if it provides more energy than it consumes (see, for example, Slesser, 1978; Slesser and Lewis, 1979). This type of assessment is referred to as net energy analysis.

3.4.1 Background

Energy analysis is a methodology whereby the energy required to manufacture a good, or create a service may be computed. It takes into account both direct and indirect energy use. To determine the primary energy inputs needed to produce a given amount of product or service, it is necessary to trace the flow of energy through the relevant industrial system. This idea is based on the First Law of Thermodynamics – that is, the principle of conservation of energy or the notion of an energy balance applied to the system (Hammond, 2004). It leads to the technique of First Law or 'energy' analysis, sometimes termed 'fossil fuel accounting' (Roberts, 1978).

A principal aim of energy analysis is thus to establish the total or 'gross' energy requirement (GER) of a product or service (Slesser, 1978). Other related aims include identifying energy-intensive activities or fuel/electricity-saving potential, and providing a physical (as opposed to financial) basis for energy forecasting studies (Allen, 2009; Leach, 1975; Roberts, 1978). It is also particularly useful for comparing the energy efficiency of different bioenergy conversion methods.

Energy analysis developed largely in response to concerns about resource depletion before receiving significant interest due to the oil price fluctuations of 1973 (Slesser, 1978). Most of the energy terminology derives from the formal establishment of the principles of energy analysis in the 1970s. Its present basis emerged from the publication of an internationally-agreed set of conventions (IFIAS, 1974). For further detail on the background to energy analysis, see Allen, 2009; Slesser, 1978; and Roberts, 1978. Net energy analysis can be viewed as part of an LCA study as the data collected in the LCI and system boundary is sufficient to calculate net energy analysis metrics (see Chapter 9).

3.4.2 Conventions, definitions and metrics for net energy analysis

When undertaking a net energy analysis, a variety of methods and conventions may be applied; therefore the chosen procedures should be both explicit and consistent with the aims of the study. Owing to this variation, it can be difficult to compare the results of different studies. Primary energy, delivered energy and useful energy, along with primary electricity and secondary electricity are defined in the glossary. The conventions, definitions and metrics applied within the present study are outlined below.

3.4.2.1. Gross Energy Requirement

'Gross Energy Requirement' (GER) can be defined as the sum of all the primary energy [expressed as thermal energy (enthalpy)] required to deliver an artefact, good or service. Some systems yield co-products, and then the energy inputs need to be apportioned between them on the basis, for example, of mass, energy content (calorific value), or monetary value of each co-product. Units are usually expressed in terms of the quantity of primary energy per unit of mass output (e.g., MJ/kg). In the case where the good/service is delivered energy in the form of electricity or heat the GER is defined by the 'energy requirement of energy' (see below).

Thus, wherever derived energy resources, such as secondary electricity, are used as an input they must be accounted for in terms of their primary energy requirement, in order to give the complete picture of energy required to produce and sustain the system. For example, the GER of electricity generated in a coal-fired power station would include the primary energy value of the coal combusted. This differs from the Net Energy Requirement (NER), which does not include the energy content of the original source of energy (Mortimer, 1991; IAEA, 1994). Furthermore, most evaluations exclude human labour and economic services in accordance with net energy analysis conventions (Slesser, 1978).

GER of a product was originally concerned with the depletion of fossil energy, and therefore all process inputs of material and energy which do not require the use of fossil and fossil equivalent resources were not accounted for. The GER method traditionally addresses the idea that only fossil fuels can be subject to scarcity, while natural renewable resources are unlimitedly available and therefore are not accounted for within the energy balance (Franzese *et al.*, 2009). However as nuclear and renewable energy become more widely used it is important to display GER results for these and not just the fossil primary energy consumed (see section 3.4.3.1 on Cumulative Energy Demand).

When calculating the GER, it is first necessary to define the industrial system boundary. This is analogous to the system boundary definition in LCA. To calculate the GER of a product or service, both the direct and indirect energy inputs have to be considered. Direct energy inputs are those at the point of product or service production, such as heat or work inputs during operation. These energy inputs themselves have indirect energy requirements to make them available at that point (e.g. the fuel inputs to a power station) (Slesser, 1978). Consideration is also given to the material inputs to the product or service. These materials have their own energy requirements to be accounted for: direct energy inputs for their processing and transportation and indirect energy inputs embodied in the machines producing them (Roberts, 1978).

The total energy input to any activity is equal to the sum of all direct energy inputs, indirect energy inputs and feedstocks. Systeme Internationale units are recommended for use throughout energy analysis. Hence, energy inputs of all types are measured in Joules (J), or multiples thereof (for example, Megajoules (MJ = 10^6 Joules)).

3.4.2.2. Energy Requirement of Energy

'Energy Requirement of Energy' (ERE) is the sum of all the primary energy requirements [expressed as thermal energy (enthalpy)] needed to produce one unit of delivered energy. This concept provides a rigorous way of comparing various energy sources and forms of delivered energy (Slesser, 1988). The units are usually expressed in terms of the quantity of primary energy per unit of delivered energy (e.g., MJ/MJ). The ERE is the cost: benefit ratio for the bioenergy system, and therefore needs to be significantly less than 1 if the system is to produce more energy than it consumes.

$$\text{ERE} = \frac{\text{Life cycle primary energy input (MJ)}}{\text{Lifetime delivered energy (MJ)}} \qquad \text{(eq. 3.3)}$$

3.4.2.3. Energy Gain Ratio

The 'Energy Gain Ratio' (EGR) is defined as the energy output from a generator over its lifetime divided by the life cycle primary energy input, and is therefore the inverse of the ERE. The EGR represents the number of Joules of primary energy produced per Joule of energy expended. The energy ratio needs to be greater than 1 if the system is to produce more energy than it consumes.

$$\text{EGR} = \frac{\text{Lifetime delivered energy (MJ)}}{\text{Life cycle primary energy input (MJ)}} \qquad \text{(eq. 3.4)}$$

3.4.2.4. Energy Payback Period

'Energy Payback Period' (EPP) is a further metric that can be used to assess electricity and heat generation technologies. The EPP is analogous to a financial payback period (often termed 'break-even point'), and represents the number of years that a system must operate until its energy output equals the life cycle primary energy input (Allen, 2009).

3.4.2.5. Displaced energy

When dealing with an energy-supply technology its net energy performance may be determined by comparing the energy it saves (displaces) with its energy investment (Allen, 2009). In this situation the energy-supply technology is seen to displace the established energy system that might be used instead. For example, a biomass electricity system may displace electricity produced by the UK grid. The energy output of the energy-supply technology in question is then quantified as the energy displaced from the established or alternative energy system. This 'energy displacement' concept is how a combined heat and power scheme can be said to 'save' energy; if it uses less fuel than the established system in providing the same energy services.

3.4.3 Net Energy Analysis Methodology

The main definitions and metrics needed for net energy analysis (as described above) were applied to the case studies of bioenergy systems. This section gives an overview of the net energy analysis methodology applied in this thesis.

3.4.3.1. Cumulative Energy Demand

The Cumulative Energy Demand (CED) of a product represents the direct and indirect energy use throughout the life cycle, including the energy consumed during the extraction, manufacturing, and disposal of the raw and auxiliary materials. CED is equivalent to the GER of a product or service, hence to calculate the GER the Life Cycle Impact Assessment Method (LCIAM) Cumulative Energy Demand was applied (Frischknecht *et al.*, 2007). This LCIAM expresses results in terms of MJ and thus gives the GER of a product or service.

Different concepts for determining the primary energy requirement exist. For CED calculations, one may chose the lower or the upper heating value of primary energy resources where the latter includes the evaporation energy of the water present in the flue gas (Frischknecht *et al.*, 2007). Furthermore, one may distinguish between energy requirements of renewable and non-renewable resources. The CED LCIAM distinguishes between different types of energy, where results are split into the five categories of non renewable fossil; non renewable nuclear; renewable biomass; renewable wind solar and geothermal; and renewable water. The net energy analysis results in this thesis have used all of these energy indicators, expressed in Megajoules ($MJ_{eq.}$), to calculate the GER. This is because it is useful to see the full results displayed. Given the drive towards a low carbon economy, future energy supplies will incorporate more renewable and nuclear sources. Hence this net energy analysis is forward thinking in this respect.

3.4.3.2. Applying Net Energy Analysis Metrics

CED was used to calculate the lifetime primary energy input (in $MJ_{eq.}$) in the bioenergy system case studies. From this the metrics outlined above (ERE, EGR and EPP) were calculated. Additionally the 'displaced EGR' and 'displaced EPP' were calculated based on the established energy system that was likely to be replaced. In the case of electricity, this was assumed to be the UK electricity grid. For heat, this was understood to be natural gas or heating oil. Combined heat and power (CHP) could displace a combination of the above, or a natural gas or diesel CHP plant may be displaced.

3.5 SUMMARY

The four main methodologies applied in this thesis have been presented in this chapter. Some further detail on the application of these is included in the relevant chapters where appropriate. The stakeholder survey methodology is applied in Chapter 4 which looks at the barriers to and drivers for UK bioenergy development. A resource assessment for the South West of England is completed in Chapter 5. Case studies on the life cycle assessment (LCA) of perennial energy crops are undertaken in Chapter 6. LCA methodology is further applied in Chapter 7 which focuses on the system boundaries and life cycle inventory (LCI) of a biomass gasification plant (BGP). Chapter 8 uses the LCI data to complete a LCA study of the BGP. Net energy analysis is then applied to the same BGP and the perennial energy crops in Chapter 9. Finally in Chapter 10, a combination of both LCA and net energy analysis are used to compare other energy production systems to the case studies outlined in Chapters 6 to 9.

CHAPTER 4. BARRIERS TO AND DRIVERS FOR UK BIOENERGY DEVELOPMENT

In this chapter the work performed on the barriers to and drivers for UK bioenergy development is presented. This research was originally completed by the lead authors Adams, P. and Mezzullo, W.G. The findings were first presented by the author in December 2008 at the Aspects of Applied Biology conference 'Biomass and Energy Crops III' held at DEFRA's central science laboratory (CSL) in York (Adams *et al.*, 2008). This paper, entitled 'Barriers to and Drivers for UK Bioenergy Development', was subsequently updated and published in the journal Renewable and Sustainable Energy Reviews (see Appendix A).

Further work presented in this chapter arises from a study performed for the Environment Agency by the author. This work assessed the current bioenergy utilisation in the UK and assessed different scenarios of potential development of UK Bioenergy up to 2020. This chapter therefore shows an overview of the current UK bioenergy situation, what the main barriers to and drivers for bioenergy development are, and a discussion of the future development of UK bioenergy.

4.1 BACKGROUND

A review of various UK bioenergy projects was undertaken to identify the reasons for individual success, what motivated each project, the biomass used and technology employed (Adams *et al.*, 2008). In addition, several unsuccessful projects were reviewed to understand possible reasons for not being viable projects, and what the barriers were to success. Alongside assessing individual projects, UK bioenergy development as a whole was appraised. This allowed for a 'macro' analysis of the UK Government policy drivers, alongside a 'micro' analysis of different bioenergy projects.

In the present study a number of barriers have been identified through an assessment of different bioenergy project case studies. Various incentives, or 'drivers', for bioenergy development are also assessed. In order to confirm these barriers and drivers, an online questionnaire was developed for each of four main stakeholder groups: farmers/suppliers, developers, end-users and Government/policy. Respondents were asked to assess each barrier and driver, rate them in importance, and to provide any additional comments.

4.2 UK BIOENERGY POLICY

Political motivation to support bioenergy arises from individual drivers or combinations Policies designed to target one driver can be detrimental to another. For example, the RTFO was introduced primarily to reduce GHG emissions, however many of the feedstocks have been imported which may reduce energy security (RFA, 2011). The range of drivers and potential energy supplies is also reflected in the range of sectors affected by bioenergy and biofuel provision. For example, provision of feedstocks could be the responsibility of three quite distinct sectors – agriculture, forestry and waste disposal – each of which are governed by separate policies, environmental regulations and Government departments (Royal Society, 2008). Hence there is a need to better understand these policy implications.

In May 2004 the Royal Commission on Environmental Pollution (RCEP) published a report on Biomass as a renewable energy source. In the report, the Commission found that the opportunities for using biomass to reach CO_2 reduction targets for the UK are significant; and recommended that energy policy should promote the development of the biomass sector to help a low-carbon economy and invited the Government to improve measures to encourage biomass as a long-term, stable and secure option for renewable energy (RCEP, 2004). The report concluded that despite the wide variety of biomass resources in the UK, the failure to realise the potential of these resources is due to a lack of effective, co-ordinated Government policy to establish investor and farmer security and to develop the supply chain (RCEP, 2004).

The initial UK Government response expressed agreement with some of the RCEP's points. This led to a Biomass Task Force being set up to help Government and industry develop biomass energy in support of renewable energy targets and sustainable farming and forestry and rural objectives (Gill *et al.*, 2005). The Biomass Task Force proposed various recommendations to help develop the UK bioenergy industry. The UK Government responded by introducing several policies and schemes in recent years which have provided different incentives for bioenergy development (see Chapter 1). In May 2007 the UK Biomass Strategy outlined the Government's plan to (DEFRA, 2007a):

- Realise a major expansion in the supply and use of biomass in the UK;
- Facilitate the development of a competitive and sustainable market / supply chain;
- Contribute to overall environmental benefits and the health of ecosystems through the achievement of multiple benefits from land use;
- Facilitate a shift towards a bio-economy through sustainable growth and development of biomass use for fuels and renewable materials;
- Maximise the potential of biomass to contribute to the delivery of climate change and energy policy goals: to reduce CO_2 emissions, and achieve a secure, competitive and affordable supply of fuel.

As part of this strategy the Government acknowledged that increasing the supply of biomass will have implications for land use, biodiversity, landscape and a range of other environmental factors (DEFRA, 2007a). In July 2009 the UK Government set up the 'Office for Renewable Energy Deployment' (ORED) to help stimulate investment and develop supply chains in all renewable energy technologies, with a specific objective to encourage and enable more use of 'sustainable bioenergy' (DECC, 2009b). This highlights the Government's desire for the UK bioenergy industry to develop, but also demonstrates that sustainable development is an integral part of this.

This review of UK bioenergy policy has demonstrated that various political incentives, or 'drivers', have been created to encourage UK bioenergy development. The following work in this chapter aims to further research these drivers for different stakeholder groups, alongside investigating the potential barriers to UK bioenergy development.

4.3 BIOENERGY IN THE UK

In 2009 biomass electricity generation accounted for 2.8% of the UK's electricity generation, heat from biomass generated less than 1% of heat demand, biodiesel accounted for 4.2% of diesel, and bioethanol 1.4% of petroleum; the combined contribution of biodiesel and bioethanol was 2.9% of the UK's road transport fuel (DECC, 2010b). Table 4-1 outlines the biomass sources which were used to generate this electricity, heat and biofuels.

Table 4-1: Biomass sources used to generate electricity and heat and for transport fuels in the UK – thousand tonnes of oil equivalent (source: DECC, 2010b)

Biomass used to generate electricity	2005	2006	2007	2008	2009
Landfill gas	1,407	1,451	1,534	1,560	1,624
Sewage sludge digestion	153	147	165	179	209
Municipal solid waste combustion	426	479	487	507	625
Co-firing with fossil fuels	831	829	641	529	592
Animal Biomass	162	149	223	253	232
Plant Biomass	126	119	134	186	364
Liquid biofuels	-	-	-	4.8	-
Total biomass for electricity	**3,104**	**3,173**	**3,183**	**3,220**	**3,646**

Biomass used to generate heat	2005	2006	2007	2008	2009
Landfill gas	14	14	14	14	14
Sewage sludge digestion	53	45	51	52	68
Wood combustion - domestic	266	299	332	359	375
Wood combustion - industrial	93	97	101	162	165
Animal Biomass	14	25	48	42	40
Plant Biomass	92	103	109	188	203
Municipal solid waste combustion	34	34	334	32	31
Total biomass for heat	**566**	**616**	**688**	**849**	**896**

Biomass sources used as liquid transport fuels (biofuels)	2005	2006	2007	2008	2009
as Bioethanol	48	54	86	116	178
as Biodiesel	26	134	276	705	831
Total biofuels for transport	**74**	**188**	**362**	**821**	**1,009**

In the UK Government's Renewable Energy Strategy, the analysis suggested that biomass-fuelled technologies may need to provide around 30% of the UK's renewable electricity and heat generation and most of the 10% renewable transport fuel, in order to meet the EU-wide target (DECC, 2009b). The strategy estimates that to achieve up to 14% renewable heat and up to 37% renewable electricity would require around 80TWh of bioenergy (DECC, 2009b). Therefore despite rises in bioenergy use in recent years it is clear that the UK bioenergy industry will need to develop significantly over the next decade, if EU and UK Government targets are to be met.

Current patterns of bioenergy utilisation vary between the UK and some of its neighbours. In many European countries, such as Austria, Finland, Germany and Sweden, bioenergy makes a significant contribution towards total energy generation (IEE, 2007; Observ'ER, 2007). In these countries a range of financial measures and supportive policies have helped promote the use of bioenergy (Koplow, 2006; Kutas et al., 2007; McCormick & Kaberger, 2007; Thornley & Cooper, 2008). For example, renewable electricity in Germany is rewarded through a feed-in-tariff mechanism, which provides a guaranteed income and has greatly increased the uptake of bioenergy projects (Yeatman, 2006). In comparison to other countries, the UK is some way from reaching its bioenergy capacity (Observ'ER, 2006; Observ'ER, 2007; DEFRA, 2007a). The challenge facing both the UK and other EU states is to accelerate the implementation of bioenergy systems to meet EU targets for renewable energy use and reducing carbon emissions, whilst ensuring a sustainable feedstock supply.

4.4 PROJECT IMPLEMENTATION

Each bioenergy project is different as discussed in Chapter 2 section 4. Potential variations may include biomass source, location, conversion technology, etc. Nevertheless there are certain aspects which are common to all bioenergy projects. This section presents the findings from the case study review as to the key stakeholders and main aspects of bioenergy projects. From this several critical success factors are highlighted which must be achieved for project implementation. Additionally, a number of 'barriers' were identified which have to be overcome for a successful project.

4.4.1 Identify Key Stakeholders

Reasons for unsuccessful bioenergy projects can originate from any, or multiple, stages of the project's development chain. The supply chain (see Figure 4-1), considered a critical component for the success of bioenergy development (DEFRA, 2007a; Gill *et al.*, 2005), is ultimately created between the demand for bioenergy and the supply of the energy resource. The four main stakeholders that can affect a bioenergy supply chain are: feedstock supplier, plant developer/owners, Government department policy advisors and primary end-users. Suppliers are involved in the production and supply of biomass feedstock, developers are concerned with operability and implementation of bioenergy conversion plants, whilst primary end-users purchase and consume the primary biomass energy. Government/policy stakeholders are involved in guiding bioenergy development in the UK through the introduction of economic instruments and other incentives.

4.4.2 Aspects of bioenergy projects

Figure 4-1 shows the supply chain and external influences on a typical bioenergy project (adapted from Deublein & Steinhauser, 2008; Ecofys, 2005). This diagram incorporates the sequence of project stages that a developer needs to undertake.

4.4.3 Critical success factors for bioenergy projects

For a bioenergy project to be successfully implemented, a number of critical success factors have been identified (listed alphabetically):

- **End-user demand** – There must be a consumer for bioenergy produced;
- **Finance** – Capital expenditure can be significant but is essential to get the project up and running. Operational costs can vary with maintenance and feedstock prices;
- **Legislation** – Various compliance is required with local planning, environmental laws, WID, etc.
- **Secure feedstock supply** – Critical to ensure continuous project operation;
- **Stakeholder engagement** – Consultation with local community/authorities;
- **Technology** – Conversion process needs to be proven to ensure external finance, but also the long-term profitability of the project.

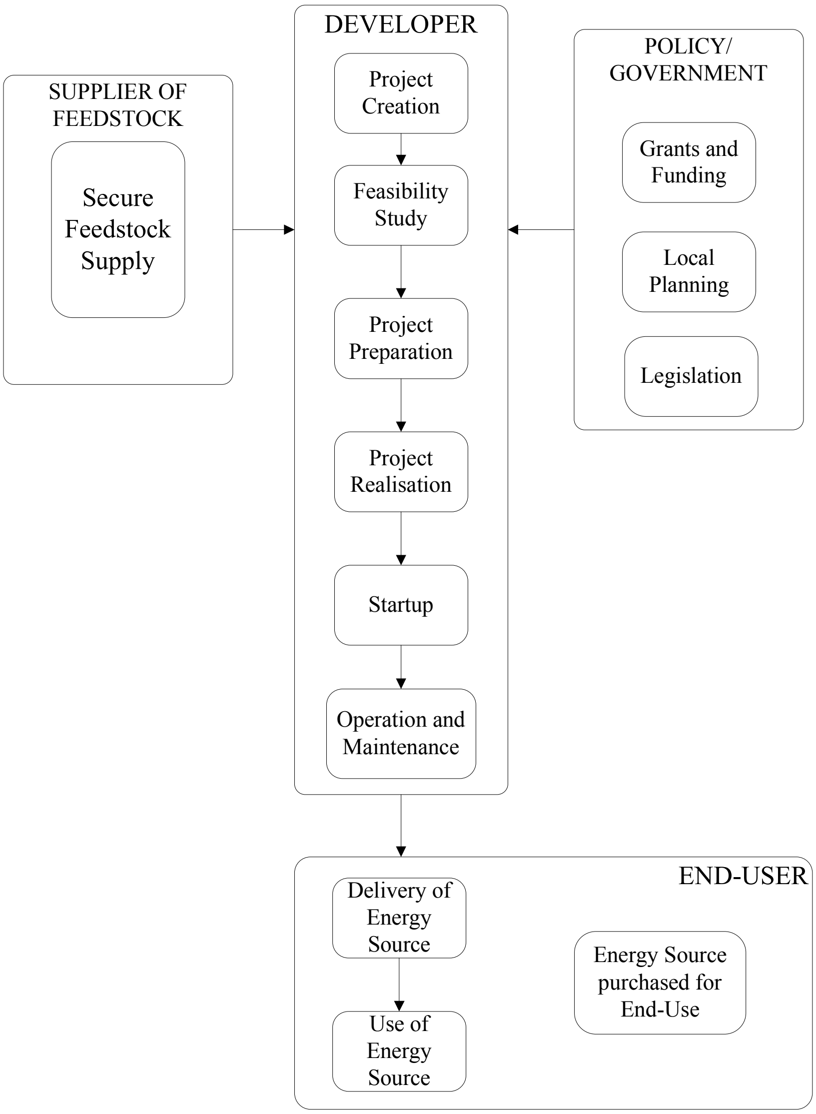


Figure 4-1: Linkage between stakeholder groups associated with bioenergy projects – Concept from (Deublein & Steinhauser, 2008; Ecofys, 2005)

4.4.4 Potential barriers to bioenergy projects

Inhibitors to UK bioenergy development can be observed via a number of Government-funded biomass energy projects that, for assorted reasons, have experienced difficulties in implementation. In 2004, Government funds of £18m were awarded to five bioenergy plants across the UK; to date none of these projects are fully operational (RegenSW, 2008). Several studies have indicated a pattern of barriers that impede the development of bioenergy. In the UK the main barriers to bioenergy projects were identified as (listed alphabetically):

- Financial problems obtaining capital for construction and during operation/lifespan of plant (Piterou *et al*., 2008);
- Increased transport around bioenergy plants (Upreti, 2004);
- Local planning approval (DECC, 2009b);
- Location of bioenergy plant – visual impacts (Upham & Shackley, 2006);
- Mistrust between local community, developers and agencies; and the credibility of developer (Upham & Shackley, 2007; Upham & Shackley, 2006);

- Other environmental impacts, for example odours, noise, etc. (McCormick & Kaberger, 2007);
- Sustainability constraints (Thornley *et al.*, 2009b)
- Technical problems associated with conversion techniques (Piterou *et al.*, 2008).

Barriers to development of bioenergy differ at varying stages of project implementation. Such stages include technical and project development; project modification; design approval and construction monitoring; performance testing and handover; and finally, operation and maintenance.

There are a large number of bioenergy 'pathways' or process routes, as discussed in Chapter 2, hence the barriers and drivers for each of these could potentially be different. Thus, the barriers to producing biodiesel from palm oil in (say) South East Asia will be different to those for the production of heat from farm waste in the UK. However, in the present study these different pathways have not been specifically distinguished as the research was aimed at indentifying the more general barriers and drivers to bioenergy. This is in accordance with previous UK Governmental bioenergy studies and strategies for bioenergy production (see, for example, DEFRA, 2007a; Gill *et al.*, 2005, DECC, 2009b).

4.5 BARRIERS AND DRIVERS FOR EACH STAKEHOLDER GROUP

Having described each of the four main stakeholder groups, the next step was to propose the barriers and drivers for each group. Barriers and drivers were identified from existing literature, and from the analysis of case studies from UK bioenergy projects, as presented above. This section therefore sets out the proposed barriers and drivers which were subsequently used for the stakeholder survey.

4.5.1 Barriers and drivers for biomass feedstock suppliers

The barriers and drivers that were specified in the questionnaire for feedstock suppliers are reproduced in Table 4-2. There could be a perceived difficulty of growing novel energy crops in comparison to other food crops (Mattison & Norris, 2007), although farmers may be willing to invest in energy crops to diversify the market. Low or uncertain returns on investment could also be seen as an important barrier to the development of bioenergy feedstock (Sherrington *et al.*, 2008). Uncertainties over grant or funding support are a potential barrier to the take-up of biomass feedstock. It has been suggested that without financial support the uptake of bioenergy crop production would be considerably lower (Sherrington *et al.*, 2008). Environmental impacts such as loss of biodiversity effects may be viewed by farmers as a barrier towards feedstock development.

Table 4-2: Barriers and drivers to the development of bioenergy for feedstock suppliers

Barriers	Drivers
Competition vs. other investments. Lack of feedstock experience. Limited/uncertain return on investment. Negative environmental impacts of feedstock. Perceptual challenges of feedstock. Physical resource limitations (land availability). Resource intensive feedstock. Uncertainties of financial support. Unclear legislative limitations. Unsettled bioenergy market (unreliable buyer).	Attractiveness of a growing bioenergy market. Availability of financial support. Good technique for waste utilisation. Market diversification. Meeting Governmental energy/carbon/waste targets. Other environmental benefits (other than CO2 reduction). Possible reduction in carbon emissions. Profitable return on investment. Reduction in fossil-based fuels.

4.5.2 Barriers and drivers for biomass process plant developers/owners

Barriers to the development or ownership of a bioenergy project (see Table 4-3) include the adoption of a conversion technology that could either be financially or practically unproven. This barrier is considered applicable to many bioenergy pathways. Other barriers include a lack of local feedstock supply, thereby forcing developers to import from outside the UK. The import of wood-pellets into the UK signifies the lack of feedstock supply within the country (Junginger *et al.*, 2008). Financial considerations clearly give rise to a number of potential drivers and barriers to the development of bioenergy projects. Proposed drivers for bioenergy include Governmental support mechanisms (economic instruments and other incentives). However, uncertainties about the financial costs associated with operation, and maintenance of bioenergy plants, as well as the cost of end-product distribution were all anticipated to be significant barriers (Piterou *et al.*, 2008).

Table 4-3: Barriers and drivers to the development of bioenergy for process plant developers/owners

Barriers	Drivers
Competition vs. other renewable energy options. Lack of feedstock supply (resource availability). Low primary-end-user demand. Perceptual challenges of bioenergy plant. Planning and installation Issues. Possible negative environmental impacts. Uncertain development and operational costs. Uncertainty of conversion technology/ equipment. Unclear and complex legislative issues.	Availability of financial reward/support mechanisms. Bioenergy supply consistency vs. other intermittent energy options. Bioenergy use versatility. Increased bioenergy interest from end-user. Market diversification/opportunity. Possible reduction in carbon emissions. Reduction in fossil-based fuels. Variety of feedstock use for bioenergy (resource diversification).

4.5.3 Barriers and drivers for primary end-users of bioenergy

Primary end-users of bioenergy range from electricity suppliers (seeking to utilise ROCs) to domestic heating users (wanting to reduce dependency of fossil-based fuels and, arguably, wishing to improve environmental impacts associated with energy use). The associated barriers (see Table 4-4) include financial implications of bioenergy. High buying costs of biomass resources, with respect to other sources of fossil-fuel derived energy (or even other renewable energy options), discourage the use of bioenergy. Similarly, uncertainties within the bioenergy market, such as seasonal variability of feedstock supply, will ultimately create volatile buying costs for various types of bioenergy.

Table 4-4: Barriers and drivers to the development of bioenergy for primary end-users of bioenergy

Barriers	Drivers
Bioenergy costs vs. fossil-fuel.	Ability to penetrate most energy markets (versatile).
Infrastructure and other costs.	Bioenergy use consistency vs. other intermittent energy options.
Legislative issues.	Direct substitute of fossil-based fuels.
Low supply of bioenergy.	Good technique for waste utilisation.
Perceptual challenges of bioenergy use.	Help in supporting Governmental schemes.
Preferential over other renewable energy options.	Investment opportunity into renewable energy.
Seasonal effects of bioenergy supply.	Positive effects on image.
Uncertainty of adaptability.	Possible reduction in carbon emissions.
Unsettled/changing bioenergy market.	Reduction in fossil-based fuels.

4.5.4 Barriers and drivers for Government/policy

Table 4-5 shows the barriers and drivers related to Government/policy stakeholders. These are linked to how these 'actors' would support or discourage the use and development of bioenergy.

Barriers specified in the questionnaire for this stakeholder group include the competition that bioenergy could face against other renewable energy options, such as wind energy or solar. Another barrier is the postulated link between bioenergy crop growth and the rise in food crop prices (Doornbosch & Steenblik, 2007; OECD-FAO, 2007). Obtaining feedstock from 'unsustainable' sources will also have negative implications on the perceived environmental benefits of using bioenergy. This could ultimately hinder the attainment of Government-set targets of carbon reductions, and the objective of improving fuel security (DTI, 2007). Financial support mechanisms, however, may result in the adoption of unproven conversion technologies. They might then ultimately not yield a suitable return on investment.

Table 4-5: Barriers and drivers to the development of bioenergy for Government/Policy stakeholders

Barriers	Drivers
Competition vs. other renewable energy options.	Bioenergy supply consistency vs. other intermittent energy options.
Lack of feedstock supply (resource availability).	Bioenergy use versatility.
Legislative Issues regarding bioenergy.	Decentralisation of energy capability.
Negative effects on food crop prices.	Good technique for waste utilisation.
Negative global environmental impacts.	Increase rural development and economy.
Negative local environmental impacts.	Increased fuel security.
Perceptual challenges.	Possible reduction in carbon emissions.
Uncertainty of conversion technology/ equipment.	Reduction in fossil-based fuels.
	Variety of feedstock use for bioenergy (resource diversification).

A variety of Governmental strategies seek to encourage the development of bioenergy (DEFRA, 2007a; DECC, 2009b). These are aimed at: increasing energy security, reducing carbon emissions, and reducing overall dependency on fossil fuels. Incentives for the development of bioenergy (such as economic instruments of various types) are seen as important factors from a Government/policy perspective. Parallel to these drivers are incentives for diversifying the use of waste. Reducing waste to landfill through the Landfill Directive, for example, encourages the use of biomass waste for energy purposes (DEFRA, 2007c).

4.6 STAKEHOLDER SURVEY

An online stakeholder survey was carried out for each of the four stakeholder groups in a similar manner to the risk assessment of the UK electricity sector by (Hammond & Waldron, 2008). Having proposed the main barriers and drivers for each stakeholder category, four online questionnaires were constructed (one for each group). The online questionnaire postulated a list of possible barriers and drivers to the development, use and support of bioenergy, as outlined in section 4.5. Respondents were asked to rate how important each barrier and driver was for the development of bioenergy. The questionnaires offered the respondents five choices: 'critical' importance, 'very' important, 'moderate' importance, 'unimportant' or 'undecided'. They could also indicate if they were 'undecided', and also had the opportunity to add other barriers or drivers.

The study focused on more overarching aspects of development as opposed to specific (or plant-dependent) issues. Responding stakeholders in each group were identified through the literature, and from attending a number of UK bioenergy-related events during 2007-2008. Respondent suitability was assessed based on previous experience or a relevant interest in the bioenergy field. The respondents were contacted via emails with a covering document explaining the details of the research. The email incorporated a web link directing them to the online survey. Once the questionnaire was completed, the respondents submitted their assessments; these were stored in an online database. Data were collated into the four stakeholder categories, and analysed to determine the most important barriers and drivers to UK bioenergy development.

4.7 RESULTS ANALYSIS

4.7.1 Online survey outturn

A summary of the key findings from the online stakeholder survey is outlined below, along with an interpretation and implications of the results. The results are presented in the form of 'spider web' diagrams in Figures 4-2 to 4-9. The response rate of the questionnaire was just over 45%, with a total of 72 responses from across the UK bioenergy industry. This is a relatively good outcome in comparison, for example, with the online risk survey of the UK electricity sector by Hammond and Waldron (2008). There the response rate was one third of those originally asked to complete the questionnaire.

The spider web diagram is a graphical method of displaying multivariate data in the form of a two-dimensional chart of several variables represented on axes starting from the same point. Each axis therefore represents one barrier or driver, with the distance away from the centre point indicating the percentage of respondents. The four main choices (i.e.

critical/very/moderate/unimportant) are layered on top of each other with the highest response rate for each barrier/driver remaining on top.

4.7.2 Farmers and biomass feedstock suppliers

4.7.2.1. Barriers to an increase in UK biomass supply

The results show that almost all (85%) of farmers and suppliers see competition from other investments as a 'critical' or 'very important' barrier to increasing the supply of biomass feedstock (see Figure 4-2). The primary reason given was that, at present, annual food crops remain more economical than perennial energy crops. This finding is consistent with a recent study on the domestic supply of perennial energy crops by Sherrington *et al.* (2008), who found that there was uncertainty about the financial viability of energy crops in the short term. In addition, there were uncertainties surrounding the production costs, potential yields, and market prices. Energy crop prices were viewed as being low compared to wheat (see also (Sherrington *et al.*, 2008). There are also risks associated with being tied into long-term contracts, as this is not the traditional mechanism for farming. Uncertainty over grant funding was identified as the second most important barrier. Few farmers would consider growing energy crops without a grant regime, due to high up-front capital costs and the uncertainty over net income.

Financial return on investment was the third most important barrier identified by respondents in this group, due to the potential impacts on a farm's business structure. Profit margins for biomass feedstock in the UK can be low or even negative, resulting in a requirement for Government support mechanisms (see section 4.2). Land availability was identified as the next most important barrier, with farmers likely to grow energy crops on their least productive land (according to Sherrington *et al.*, 2008). In the short term, first generation crops, such as oilseed rape and wheat, require large areas to produce sufficient amounts of bioenergy to meet UK targets. For example, it is estimated that between 1.2 Mha and 1.5 Mha of UK land will be needed to meet the original 5% RTFO target (DEFRA, 2007a; Hammond *et al.*, 2008a). This highlights the heavy reliance on land-use to produce first generation energy crops. Alternative biomass sources, such as waste, therefore need to form an integral part of the future development of UK bioenergy (Hammond *et al.*, 2008b). This will help to reduce the need for direct and indirect land-use change, as well as alleviating the fuel versus food issue. However, it is difficult to collect large quantities of biomass wastes, due to its dispersed nature.

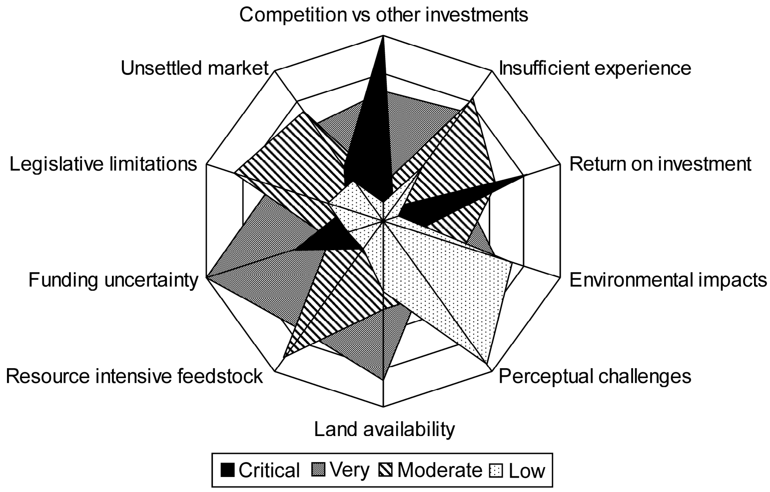


Figure 4-2: Barriers to bioenergy development according to farmers/suppliers of biomass feedstock

4.7.2.2. Drivers for an increase in UK biomass supply

The ability to 'make a profit' was by far the most important driver for farmers, and biomass feedstock suppliers (see Figure 4-3), with 90% of respondents stating this was either 'critical' or 'very important' to the development of energy crop production in the UK. This underpins the necessity of energy crops and other biomass feedstock being economically viable. Perennial energy crops are a significant change from the more traditional annual farming cycle, as they make it much harder to adjust production to the requirements of market conditions and prices. This perhaps explains the present low uptake of crops under the Energy Crops Scheme (DECC, 2009b). If such crops can become economical in the long-term, then their introduction offers a lifestyle choice for farmers. There are fewer annual operations associated with perennial energy crops and so some farmers may opt for a slightly lower income in return for a less arduous crop management regime.

Farmers and suppliers identified climate change mitigation and reducing fossil fuel dependency as imperative over the longer term (see again Figure 4-3). This is perhaps due to their reliance on fuel for machinery, which affects several farming operations. These drivers were also recognised by Sherrington *et al.* (2008) as a potential motivation to grow energy crops.

The fourth most important driver was the potential attractiveness of the growing bioenergy market. Given that the most important driver was to make a profit, with climate change and fossil fuel depletion also considered important, it follows that farmers and suppliers may be driven by entrepreneurial motives towards renewable energy, in order to secure a more diversified market.

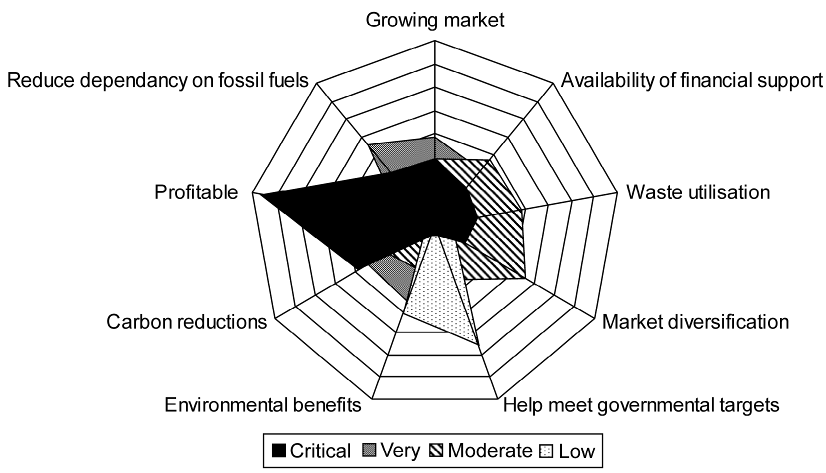


Figure 4-3: Drivers to bioenergy development according to farmers/suppliers of biomass feedstock

4.7.3 Developer/owner stakeholders of bioenergy projects

4.7.3.1. Barriers to developing bioenergy projects

Technology is identified as the most critical barrier (see Figure 4-4), as many developers found that some biomass technologies were unproven, commercially unviable, or there was a lack of UK knowledge and experience. This is perhaps a reflection of the fact that the UK's bioenergy industry is still in it's relative infancy. As previously discussed (see section 4.4), there have also been a number of failed or slow developing bioenergy projects in the UK. However, when compared to some other EU countries, it is apparent that for many bioenergy production pathways, technology is not always the most important barrier. McCormick & Kaberger (2007) found that learning processes and optimising systems were important. They argued that there were no technical issues that represent overriding barriers to bioenergy development.

Development and operational cost were identified as the second most significant barrier, which is understandable when introducing new technologies. It is likely that, as the bioenergy industry expands in the UK, 'economies of scale' can be achieved and costs will reduce. However, the logistics of biomass systems require feedstocks to be inexpensive to produce and transport in comparison to fossil fuels. Associated with this, depending on their energy content and density, they are often required to be located close to the conversion point to minimise transport costs. High capital costs are associated with most bioenergy technologies, and respondents to the survey also identified uncertainty over, or lack of, grant funding as an important 'other' barrier, which is closely linked to costs of production.

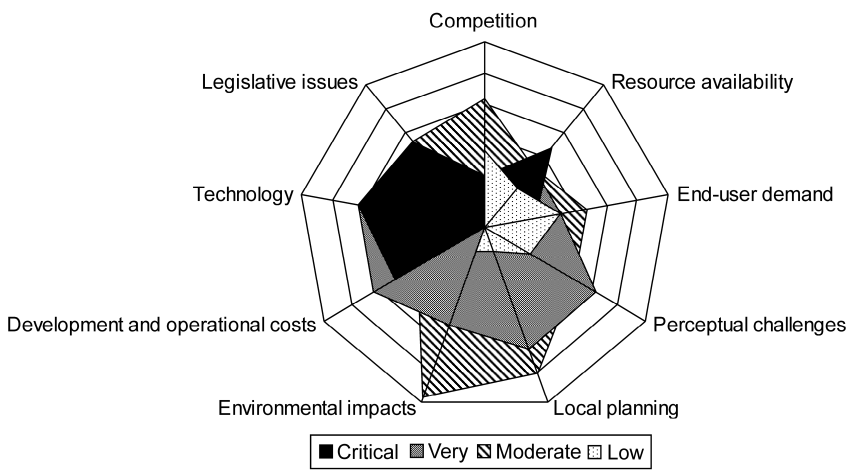


Figure 4-4: Barriers to bioenergy development according to developers/owners of bioenergy projects

For biomass electricity production, both technology and cost barriers could be reduced in the UK with the introduction of banding under the Renewables Obligation (RO). Since 1st April 2009, emerging technologies, such as anaerobic digestion, gasification and pyrolysis, now receive two Renewable Obligation Certificates (ROCs) per MWh of electricity produced, which is twice the support previously received (Ofgem, 2009). The main objectives of the RO are to incentivise renewable electricity in the UK, and to provide longer term confidence for investors. Banding of the RO has provided more support for technologies that are currently further off from commercial deployment.

Legislative issues are an important barrier for developers as they need to be familiar with a variety of regulations, depending on the technology they adopt. For example, they may need to be familiar with Integrated Pollution Prevention and Control (IPPC), Renewables Obligation, Renewable Transport Fuels Obligation (RTFO), and local planning requirements. If using waste as a feedstock, developers also need to be aware of the Waste Framework Directive and the Waste Incineration Directive (EU, 2006). Compliance with this range of legislation can be complex and costly.

Resource availability was identified by respondents as the fourth most important barrier for developers. Clearly markets for biomass face competition from other industries, such as food, chemicals, polymers and fibres. In particular, energy crops face direct competition for land from food and feed crops (RFA, 2008). RCEP and the Biomass Task Force in the UK identified the fuel supply chain as a key barrier to bioenergy development (Gill *et al.*, 2005; RCEP, 2004). Developers increasingly need to devise flexible approaches to feedstock supply in response to changing market conditions.

4.7.3.2. Drivers for developing bioenergy projects

Financial reward and support are the primary drivers for bioenergy developers (see Figure 4-5) in a similar manner to farmers/suppliers. Market opportunity is an important driver for developers as they can see the business case for entering an expanding bioenergy market; without this it is unlikely that developers would invest in bioenergy schemes. The desirability of climate change mitigation and reducing dependency on fossil fuels were the third and fourth most important drivers respectively. This was again similar to the views expressed by farmers/suppliers.

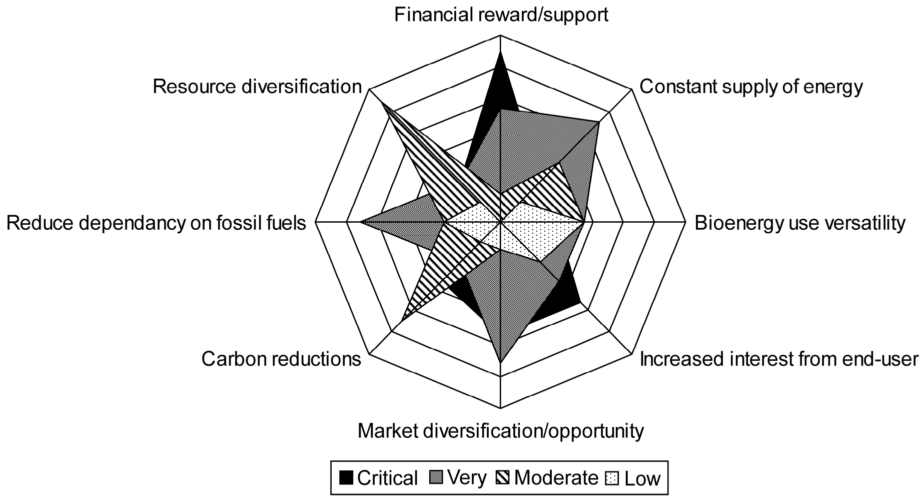


Figure 4-5: Drivers to bioenergy development according to developers/owners of bioenergy projects

4.7.4 Primary end-user stakeholders of bioenergy

4.7.4.1. Barriers to an increase in the end-use of bioenergy

Consumers and businesses often make buying decisions primarily based on cost. This is demonstrated in the survey with nearly all respondents (88%) stating that the high purchase costs of bioenergy, in comparison to fossil fuels, was a 'critical' or 'very important' barrier (see Figure 4-6). Compared to the other barriers identified, this was the most significant, and highlights the importance of end-user economic decision-making. The development of bioenergy is therefore highly dependent on its cost competitiveness against fossil-based fuels. Generally, examples of successful bioenergy projects have competed with other sources of energy on price. For example, some biodiesel production schemes for road transport are able to compete financially with fossil-based diesel (DEFRA, 2008a). Obviously the issue of fuel poverty is related to the cost of bioenergy, as highlighted in the Energy White Paper (DTI, 2007). There the UK Government highlighted the need to address the negative consequences of rising energy prices on low income consumers. Successful future development of different bioenergy pathways and individual projects will therefore depend, for all these reasons, on the ability to compete long-term with fossil-fuel prices.

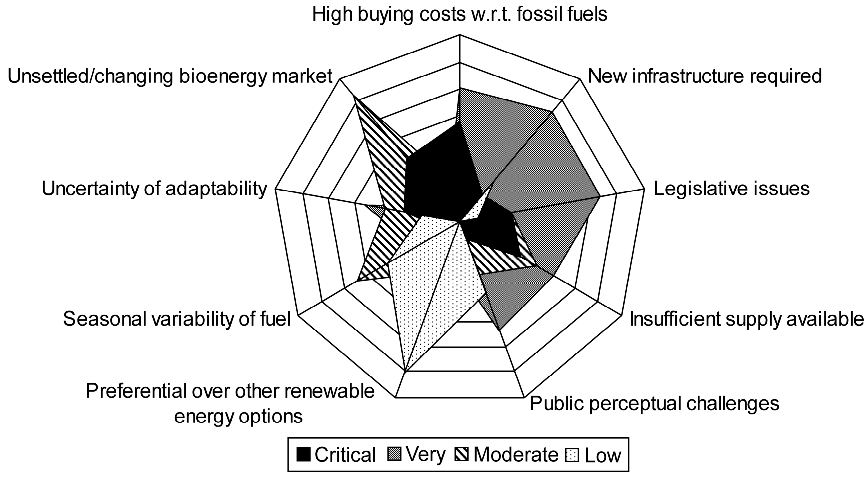


Figure 4-6: Barriers to bioenergy development according to primary end-users of bioenergy

Legislative issues, such as Government policy or international standards were also identified by end-users as important. This is perhaps a reflection of the multiplicity of legislative interventions, which affect different aspects of bioenergy. New infrastructure requirements were also viewed as an important barrier. These include: new biomass heat installations, storage requirements for co-firing, or cars requiring engine alterations to accept higher levels of biofuel blending (Hammond *et al.*, 2008a). This new infrastructure will require capital investment and may not always be practical or economic. Uncertainties surrounding adaptability are also important, for example the limits for co-firing or blending of biofuels.

Several end-users (as with developers and suppliers) identified insufficient available supply as their fourth most important barrier. This finding is repeated across each stakeholder group, and is closely linked (or cross-related) with the economics of bioenergy production. Where supply fluctuates over time, so does the cost of bioenergy. End-users will usually require a constant supply of energy resource, which is available on demand. Where bioenergy cannot offer this, it is unlikely that the end-user will switch away from their existing sources of energy. The challenge of public perception perhaps reflects the significant media interest in bioenergy over recent years. Much has been written about first generation biofuels and the competition for land with food crops (e.g. Doornbosch & Steenblik, 2007; OECD-FAO, 2007; RFA, 2008). Bioenergy has also been criticised as a potential cause of deforestation, and for disturbing carbon sinks, such as peatlands and tropical forests (Royal Society, 2008). Whilst this could be true in some cases, this is often not the case and the mixed media messages contribute to a public perception barrier. The public are also often opposed to having bioenergy projects near to where they live. For example, the phrase 'Not In My Back Yard' (NIMBY) is often associated with biomass energy projects (Upreti, 2004; van der Horst, 2007).

Other barriers identified by respondents include a lack of vehicle manufacturer support, e.g. warranties being voided on biodiesel blends greater than 5%; difficulties securing long-term contracts for feedstock; security of new technology demonstration projects; and insufficient knowledge or experience of bioenergy.

4.7.4.2. Drivers for an increase in the end-use of bioenergy

Reducing dependency on fossil fuels, directly replacing particular fuels with bioenergy resources, and reducing carbon emissions are the most important drivers in this category of stakeholders (see Figure 4-7). End-users noted the implications of varying oil, electricity and gas prices, and there seemed to be an increased awareness of climate change, energy security and fossil fuel depletion issues. Such end-users are therefore increasingly driven by a need to find alternative sources of energy, which are both renewable and produce reduced levels of carbon and other greenhouse gas emissions. Good examples of this include biodiesel for cars and woodfuel for household heat.

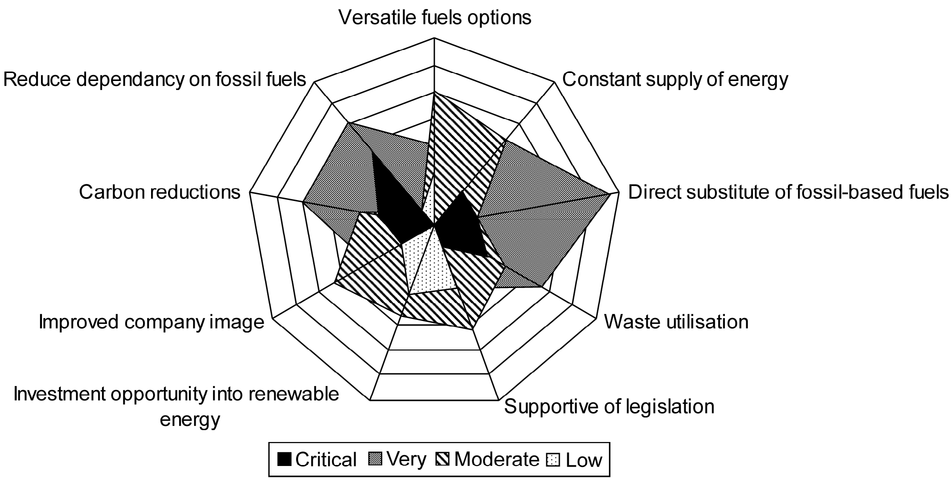


Figure 4-7: Drivers to bioenergy development according to primary end-users of bioenergy

4.7.5 Government/policy stakeholders for bioenergy development

4.7.5.1. Barriers to supporting the use and development of bioenergy

In comparison with the other stakeholder groups, the barriers for Government and other policy-makers are much more evenly distributed (see Figure 4-8). Resource availability is considered the most significant barrier, since there is limited unused, but productive land available in the UK. Therefore concerns arise over competition with food crops and reliance on imports to meet targets. This in turn means that the sustainability of the biomass resource is open to question. Rises in food crop prices were identified as an important barrier, and this is subject to an ongoing debate. It has become apparent that the increased demand of feedstocks for bioenergy has some impact on food prices (OECD-FAO, 2007). However, there are other factors that affect food bioenergy developments, both in the UK and elsewhere.

To make a major contribution to the UK energy supply, this group considered advanced conversion technologies to be essential. In the case of liquid biofuels, the Gallagher review found that second generation technologies to be immature, currently expensive, and required specific incentives for their development (RFA, 2008). This is similar for other bioenergy pathways. Significant development of biomass supply chains is also necessary in order to increase the supply of bioenergy in the UK. Competition from other renewable sources of energy is very important, as Governments must make decisions on where to direct their limited financial resources to help meet the renewable energy targets.

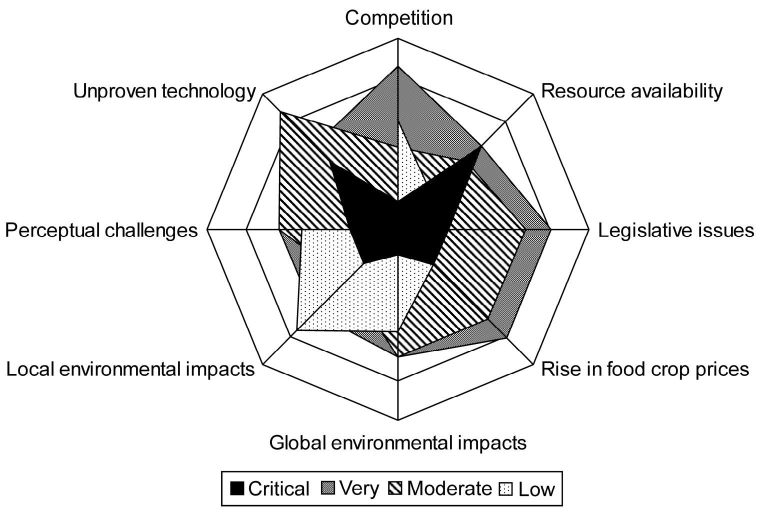


Figure 4-8: Barriers to bioenergy development according to Government/policy stakeholders

Several 'other' barriers were identified by respondents. The most important of these is the lack of skilled or trained workers in the bioenergy field. In comparison to more developed bioenergy industries, such as those in Germany, Austria or Finland, the UK lacks sufficient specialists, such as installers, operators, and maintenance engineers. Therefore, a large increase in skilled bioenergy workers will be required if the UK is to meet its renewable energy targets via a significant utilisation of bioenergy resources. This is also highlighted in other reports, such as that by the Biomass Task Force (Gill *et al.*, 2005) and more recently in the UK Renewable Energy Strategy, which expects up to half a million jobs in the British renewables sector by 2020 (DECC, 2009b).

4.7.5.2. Drivers for supporting the use and development of bioenergy

Reducing dependency on fossil fuels and reducing carbon emissions are the two most important drivers for Government and policy-makers (see Figure 4-9). Increased fuel security and much better utilisation of waste are also considered as very important. These drivers coincide with those outlined in the recent Government strategies, such as the Energy White Paper (DTI, 2007), the Waste Strategy for England (DEFRA, 2007c), and the UK Biomass Strategy (DEFRA, 2007a). The increasing price of oil and other non-renewable fuels was identified by several respondents as an important 'other' driver for increasing the use of bioenergy. Another driver is the relative cost of disposing of waste, which includes landfill tax and gate fees. Both of these drivers are obviously economically driven.

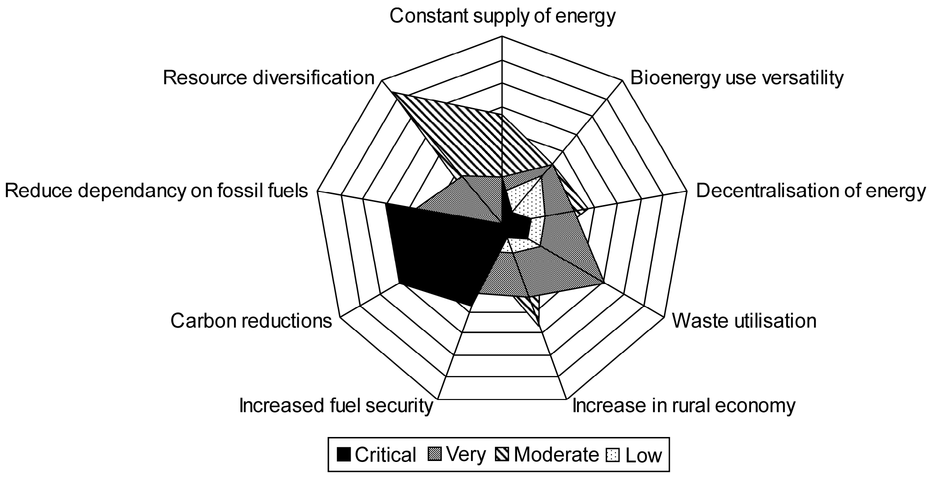


Figure 4-9: Drivers to bioenergy development according to government/policy stakeholders

4.7.6 Discussion and Interpretation of Findings

Since the results have been discussed above in the results analysis, further discussion, interpretation of the findings, and potential limitations of this research are included in the final discussion (see Chapter 11).

4.8 FUTURE UK BIOENERGY DEVELOPMENT

It is always very difficult to predict the future due to the various uncertainties and assumptions involved. However it is possible to assess the different possible scenarios of UK bioenergy development in a qualitative way, rather than attempting to quantify this. The scope of this research is limited to a discussion of some of the ways the barriers identified may be overcome, what impact this may have, and the effect of the various different influences on development.

4.8.1 Overcoming the barriers

For the UK to maximise its bioenergy potential, the barriers identified in this chapter should be addressed. The Government can influence the supply chain, by introducing economic instruments and other incentives (Adams *et al.*, 2008; Thornley & Cooper, 2008). Table 4-6 presents the main barriers for the three stakeholder groups integral to the supply chain (farmers/suppliers, developers, end-users) as identified in the present study; and ways in which the Government may attempt to overcome these.

Table 4-6: Main barriers to bioenergy development and ways in which the Government may overcome barrier

Main barriers	Possible ways Government may overcome barrier
Farmers/suppliers	
Finance – investment & funding	Provide increased grants/funding, green investment bank; Increase end-use incentives (e.g. FIT, RHI) to increase market demand and value of feedstock; Provide long term market signals to encourage investment.
Land available	More incentives for utilising waste as a resource; Support research into advanced conversion techniques, ways to increase yield, and more efficient production.
Developers	
Technology	Support investment into research & development; Provide skills, training, expertise through education; Support joint ventures with overseas companies, universities, etc. with technical knowledge.
Development & operational costs	Provide capital grants or development loans; Incentivise bioenergy generation by initiatives such as ROCs, FIT, RHI, etc.
Legislation	Simplify legislation and provide support for companies to understand and comply with rules and regulations.
Resource availability	Join up supply chain to ensure sufficient resource available; Prioritise support for projects where resource is located; Increase the use of waste for energy purposes.
Perceptual challenges	Education, positive case studies, community ownership, etc.
End-users	
High buying costs	Provide subsidies, tax-breaks for bioenergy; FIT and RHI.
New infrastructure requirements	Provide capital grants or loan for purchase of infrastructure; Encourage schemes like district heating so costs are spread.
Legislation	As above, simplify and provide ongoing support.
Insufficient supply	Encourage use of waste, demand reduction, etc.

Table 4-6 is not an exhaustive list and the measures suggested can not guarantee an increase in the uptake of bioenergy projects. Indeed, in a recent review of different policy instruments for the promotion of bioenergy in Germany, Italy, UK and Sweden, Thornley & Cooper (2008) found that Government policies have had varied levels of success. Nonetheless it is clear that Government intervention has worked in some situations recently. For example, since the introduction of the Renewable Transport Fuel Obligation (RTFO) in 2008, the production of bioethanol and biodiesel has notably increased; up from less than 1% of transport fuels in 2005 to 2.9% in 2009 (see Table 4-1).

Government intervention is not the only way is which barriers may be overcome. A clear example of this is the bank's willingness to provide finance for bioenergy projects, as most bioenergy schemes require significant capital expenditure up-front to finance the projects. Technological barriers are often addressed by private companies who develop new technologies. It is apparent, therefore, that it is not just the Government which will affect the UK bioenergy industry.

4.8.2 Scenarios of potential UK bioenergy development up to 2020 and beyond

This section highlights some different possible scenarios of how the UK bioenergy industry may develop over the next decade. This does not attempt to highlight every possible eventually, but instead provides a summary of some of the main influences. Table 4-7 gives a qualitative overview of different scenarios of development, and the effect they may have on the UK bioenergy industry.

Table 4-7: Different scenarios of UK bioenergy development

Scenario	**Potential effect on UK bioenergy industry**
Low fossil fuel prices (oil, gas, etc.)	Development limited as bioenergy cannot compete economically, significant Government support would be required to meet targets.
High fossil fuel prices (oil, gas, etc.)	Bioenergy industry likely to expand quickly as end-users search for alternatives and suppliers/developers seek profit. Less Government support needed but targets could be met.
Low commodity prices (wheat, barley, etc.)	Energy crops become more economical so biomass supply for energy likely to increase, hence bioenergy industry will develop.
High commodity prices (wheat, barley, etc.)	Farmers unlikely to grow energy crops, so resource limitations mean that bioenergy industry development is restricted. Schemes which use waste may benefit though.
Low availability of finance	Investment in bioenergy schemes severely limited due to high capital expenditure required, which limits development.
High availability of finance	Banks willing to accept risk as long-term returns make bioenergy projects attractive to invest in, hence more bioenergy schemes will be realised.
Low technological advancements	First generation technologies employed which require more traditional crops which are a limited resource. Less efficient conversion means bioenergy industry develops slowly.
High technological advancements	Second generation technologies developed which increase the efficiency of conversion and diversity of feedstocks which are utilised. Bioenergy industry likely to develop quickly.

Table 4-7 has displayed some of the possible scenarios which should be considered when assessing UK bioenergy development. No attempt has been made here to quantify this, as there are too many variables involved. However, this information is useful in the resource assessment to give an indication of the future bioenergy potential.

4.9 SUMMARY

This chapter presented the results of an in depth study as to the main barriers to and drivers for UK bioenergy development. It represents a useful contribution to the knowledge base by analysing the factors affecting the success of bioenergy projects. By surveying a range of different people from the four stakeholder groups, the different barriers each group faces were identified. It was established that for farmers and suppliers, the biggest barriers faced all related to economics, with land availability also an issue. For developers there were technical, economic, legislative and resource availability barriers to be overcome, whilst end-users were primarily concerned with the relatively high purchasing cost of bioenergy when compared to fossil fuels. Government and policy advisors confirmed a range of different barriers were currently facing the UK bioenergy industry. These included the availability of land, effects of energy crop growth on food prices, economics of production, perceptual challenges and sustainability concerns.

Drivers for an increase in the uptake of bioenergy were found to be more consistent across all stakeholder groups. Reducing dependency on fossil fuels and reducing greenhouse gas emissions were all identified as critical for a successful bioenergy industry. For developers and suppliers obtaining a return on investment was an essential driver. End-users were also motivated by alternative energy sources to fossil fuels being provided and the minimisation of waste. Government and policy advisors confirmed the key political drivers for bioenergy based on recent legislation, i.e. fuel security, climate change, renewable energy and waste reduction.

Finally an analysis of different development scenarios was undertaken to highlight whether the UK bioenergy industry would fulfil its potential, and the ways in which the Government may attempt to overcome the barriers identified. The UK Government has already introduced several of these policies with varying levels of success. Findings from other countries demonstrate that many barriers can be overcome with the right incentives and policies. However there are also several factors which are beyond the influence of Government intervention. For example, the global market for commodities, oil and gas prices, and the availability of commercial finance all have strong influences on the bioenergy industry. Similarly there are certain technological and practical barriers which may not be possible to overcome, such as the availability, type and location of sufficient biomass resources. This qualitative assessment of biomass resource constraints is used in Chapter 5 to assess the current and future available bioenergy resource.

CHAPTER 5. A BIOMASS RESOURCE ASSESSMENT FOR THE SOUTH WEST OF ENGLAND

This chapter shows that the existing biomass resource base in the South West of England is comprised of agricultural crops and residues, manures from confined livestock and poultry operations, wood and residues from forestry and product manufacturing plants, and the organic fraction of wastes. This biomass resource base has a good degree of diversity. The corollary to this characteristic is that, whilst not all biomass are equally suited to gasification or anaerobic digestion (AD), its diversity is translatable into versatility and hence affords the opportunity to produce diverse energy end-products and to develop diverse energy applications. In addition to the existing resource base, it is likely that future biomass supplies will increasingly be supplemented by energy crops, such as Miscanthus and Willow. These crops are grown for their energy content but often compete with other crops for land (RFA, 2008; Royal Society, 2008). Each component of the South West resource base is characterised in this chapter.

5.1 BACKGROUND

The ultimate applicability of all biomass conversion technologies is restricted by the quantity of feedstocks that can be made available for conversion. A meaningful impact on the UK's energy supply could not be made if the feedstock supply were inadequate. Hence the utility of biomass gasification, anaerobic digestion and other conversion technologies are, ultimately, resource-limited. This chapter aims to identify which biomass resources are currently available for bioenergy production in the South West of England. A summary of stages undertaken and presented in each section of this chapter is presented in Figure 5-1.

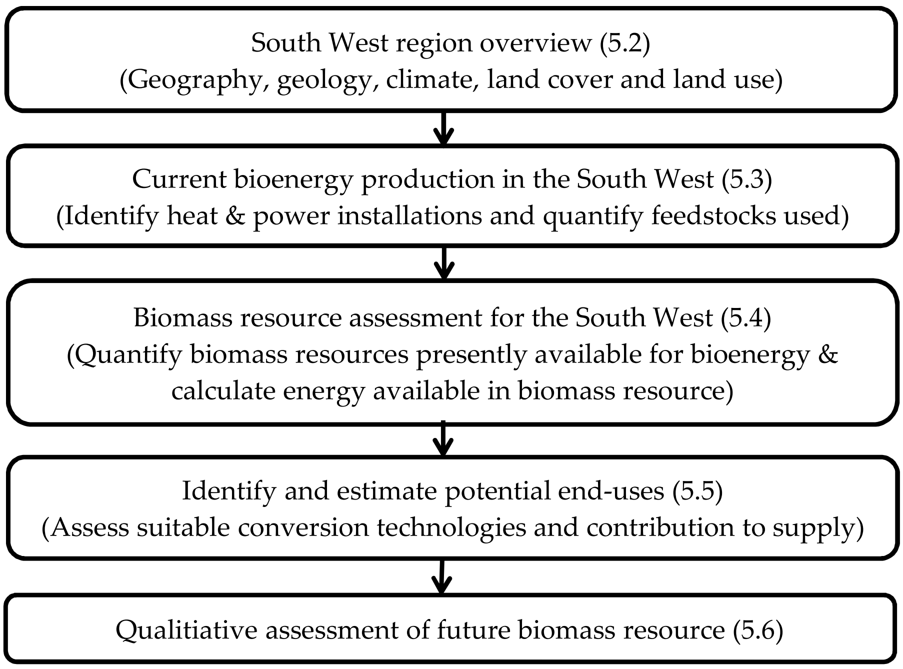


Figure 5-1: Summary of the stages undertaken and sections presented in Chapter 5

5.2 THE SOUTH WEST OF ENGLAND

To put the resource assessment in context, it is first valuable to give a description of the South West region. This allows the reader to put the resource assessment and subsequent studies into perspective. As most biomass is derived either directly or indirectly from the land it is helpful to understand the geography, geology, climate, and land cover of the region. This section therefore gives an overview of the South West region.

5.2.1 Description of the region

England is divided geographically into nine regions, the largest of which is the South West. It is nearly 400 km from end to end and covers almost 24,000 km^2 (2.4m ha) (ONS, 2010). Much of the region is sparsely populated with large rural areas, particularly south of the Mendips where the only places with large populations are on or near the South coast. Agriculture is the dominant feature of the landscape in the South West. There is little large scale industry so agriculture has shaped most man-made changes to the countryside. Another important aspect of the landscape is the national parks of Exmoor and Dartmoor, which together cover 1,600 km^2 (160,000 ha). Areas of Outstanding Natural Beauty (AONB) such as the Cotswolds, Mendips and Quantocks cover a further 4,400 km^2 (440,000 ha) (Natural England, 2009b). Consequently, the main element of competition for agricultural land in the region is not industrial development but recreation and conservation.

5.2.2 Geology and soils

Geologically the region is divided into the largely igneous and metamorphic west and sedimentary east, the dividing line slightly to the west of the River Exe (SSEW, 1984). Cornwall and West Devon's landscape is dominated by moorland and rolling hills. The East of the region is characterised by wide, flat clay vales and chalk and limestone downland. The vales, with good irrigation, are home to the region's dairy agriculture. The Southern England chalk formation extends into the region, creating a series of high, sparsely populated downs including Salisbury Plain, Cranborne Chase, the Dorset Downs and the Purbeck Hills. This is the principal area of arable agriculture in the region (SWO, 2010). Limestone is also found in the region, at the Cotswolds, Quantock Hills and Mendip Hills, where they support sheep farming (SSEW, 1984).

The South West region has a wide variety of soil types which vary greatly across the region (SSEW, 1984). The National Soil Resources Institute (NSRI) provides soil maps and data for all parts of the UK (NSRI, 2008). This includes information on soil type, drainage, fertility, habitats, texture, and land cover. The NSRI data is freely available online and therefore soils of the South West are not further characterised in this thesis.

5.2.3 Climate

Climate in the South West is varied with the main influences being altitude, proximity and exposure to the sea. It is both warmer and generally wetter than other parts of the UK (Met Office, 2009). Temperatures vary throughout the year reaching a maximum in June, July and August; with December and January being the coldest months (see Table 5-1). Rainfall can and does fall at any time of the year, although usually autumn and winter are the wettest months. These conditions favour agricultural development in terms of animal and crop farming (Scholes, 1998). When considering the growth of crops the climatic conditions are important. For example, some crops cannot tolerate frosts, or high winds. In addition the yield of a given crop will be dependent on such factors as sunshine, rainfall and temperature. Therefore further climatic data is presented in Table 5-1:

Table 5-1: South West regional average climate data 1971-2000 (source: Met Office, 2009)

Month	Max Temp (°C)	Min Temp (°C)	Days of Air Frost (days)	Sunshine (hours)	Rainfall (mm)	Days of Rainfall (>1mm)	Wind at 10m (knots)
January	8.1	1.4	11.1	50.2	72	12.5	9.2
February	8.3	1.3	10.3	68.9	55.6	10.2	9.1
March	10.6	2.7	7.5	107.6	56.6	10.9	9.1
April	12.9	3.7	5	155.4	47.3	9.2	8.4
May	16.5	6.8	0.7	193.1	48.9	8.8	8
June	19.3	9.7	0	186	57.2	8.5	7.4
July	21.7	11.9	0	205.8	48.9	6.9	6.9
August	21.5	11.7	0	197.8	56.6	8.6	6.7
September	18.6	9.6	0	139.8	64.5	10.1	6.9
October	14.8	6.9	2	101.1	67.9	11.3	7.4
November	11.1	3.6	7	70.2	65.8	11.6	7.8
December	9	2.4	9.2	46.8	83.3	12.6	8.8
Year	**14.4**	**6**	**52.8**	**1,522.7**	**724.5**	**121.2**	**7.9**

5.2.4 Land Cover and Land Use

Green space accounts for 91% of land cover in the region with over 75% of land (>1.8m ha) currently in agricultural use (DEFRA, 2009; SWO, 2010). Woodlands contribute to nearly one tenth of land cover, national parks and AONB make up the remainder of green space (SWO, 2010). Table 5-2 displays agricultural land use data which takes an average over the period 2000 to 2007 to account for yearly variations such as weather, yields, crop price, etc.

Table 5-2: Agricultural Land Use UK and South West England Average 2000-2007 (source: DEFRA, 2009)

Agricultural land use	UK Average 2000-2007 ('000 ha)	% of total UK farm land	South West Average 2000-2007 ('000 ha)	% of total SW farm land
Crops & bare fallow	4,609	25%	484	27%
Permanent grass	5,664	31%	876	48%
Rough grazing	5,611	30%	90	5%
Temporary grass	1,201	7%	208	11%
Woodland	595	3%	63	3%
Set-aside	504	3%	66	4%
All other land	272	1%	32	2%
Total agricultural land	**18,455**	**100%**	**1,820**	**100%**

5.2.4.1. Arable Land

Cereals are the most commonly grown crop on arable land in the South West region. There are 484,050 ha of total cropped area, with wheat accounting for 181,588 ha and barley 109,688 ha (DEFRA, 2009). In total cereals account for 65% of the total cropped area and 17% of the total farmed area.

5.2.4.2. Grassland

Grassland occupies a major part of the agricultural land of the UK and the South West, representing about two thirds of total agricultural land (see Table 5-2). Grassland is classified into three categories: temporary grassland (under 5 years), permanent grassland (over 5 years) and rough grazing. The major function of grassland on farms in Britain has traditionally been to supply feed for livestock, either through grazing or after conservation as hay or, more recently, silage (Soffe, 2003). This still represents the predominant use of grassland. Increased attention is now being given to other products and services that can be supplied by grassland, including using grassland as a source of biomass for the supply of energy. In the future grassland is likely to be managed for a wide range of objectives.

Permanent grassland makes up 48% of the total farmed area in the South West (DEFRA, 2009), and can be defined as grassland in fields or relatively small enclosures and not in an arable rotation (Soffe, 2003). There are many different types of permanent grassland, and as the above definition suggests, much of the area is on land not suitable to arable cropping. One reason for this is the physical limitations that impede the use of machines: the main factors are rough and steep terrain, stones, boulders and very poor drainage (Soffe, 2003). Other reasons include the higher returns farmers can obtain for certain livestock, soil type and quality, nitrate vulnerable zones and environmental stewardship.

Rough grazing accounts for 5% of the region's farmed area (DEFRA, 2009). It is defined as uncultivated grassland found as unenclosed or relatively large enclosures on hills, uplands, moorland, heaths and downlands (Soffe, 2003). According to Soffe (2003) a combination of altitude, poor soil fertility, high rainfall, and difficult access restricts the period of summer growth and potential yields. Rough grazing is therefore generally considered to be unsuitable for biomass production and is typically used for livestock farming.

Temporary grassland is grass within an arable rotation and is defined by DEFRA as being less than five years old. Its main functions include supporting the animal enterprise, being part of crop rotations (to break disease, improve fertility, break weed cycle and improve soil structure) and enable the growth of grass species suited for animal production (Soffe, 2003). Compared to both permanent and rough grazing, temporary grassland by its very nature is suitable for cultivation and machinery use.

5.2.4.3. Energy crop production

The current area of energy crops, planted under the Energy Crops Scheme (ECS) is considerably dwarfed by the total area of cereals and other food crops. There are currently 1,251 ha of Miscanthus and 39 ha of SRC planted in the South West under the ECS (Natural England, 2010), which is currently too small to be included in DEFRA national statistics.

5.2.4.4. Woodlands

There are 212,000 ha of woodland in the South West, amounting to nearly 9% of land cover (Forestry Commission, 2005). The South West has 20% of all England's woodland. Ownership of woodland is multifaceted, from the Forestry Commission managed public estate of 35,900 ha (17% of the total area) to individuals owning less than 1 ha (Forestry Commission, 2001).

5.3 CURRENT BIOENERGY PRODUCTION IN THE SOUTH WEST

This section outlines the extent of current bioenergy production in the South West region. An overview of the approach to data collection and analysis is provided in Figure 5-2:

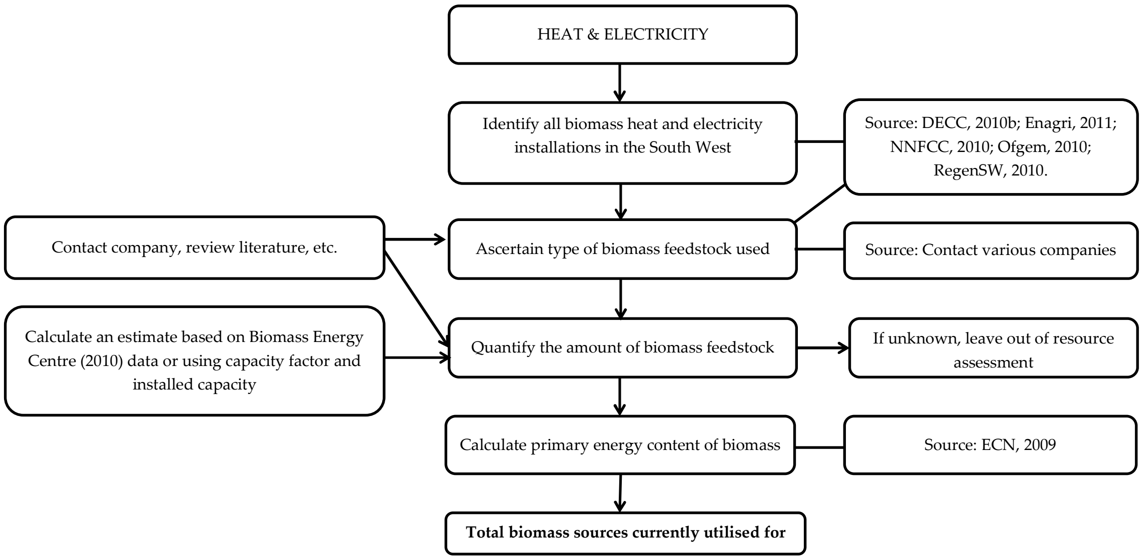


Figure 5-2: Data collection and analysis of current bioenergy production in the South West of England

Data was collected on all known biomass heat and power installations currently operating in the South West. This included data on all known (publicly available) biomass electricity, biomass heat and biomass combined heat and power (CHP) plants over 50kW. It was considered a valuable exercise to collate this information, so an estimate could be made of the biomass feedstocks currently utilised for bioenergy production in the region. The information collected did not include small-scale installations, such as domestic wood boilers, and only included data that was publicly available.

5.3.1.1. Renewable electricity installations in the South West of England

Landfill gas is the technology with the largest installed renewable electricity capacity in the South West region, with 74.8MW, representing 48 per cent of the region's total (see Table 5-3). Sewage gas CHP contributes 11.1MW (7.2%), whilst advanced waste treatment accounts for 3.4MW (2.2%) of the region's renewable electricity capacity. There were a total of 21 landfill gas sites and 16 sewage gas digestion plants identified in the region (see Appendix D). Data from these installations is available from Ofgem (2010), with further information obtained by contacting the waste management and water companies who manage these sites, and from DECC (2010b). Advanced treatment of waste plants are assumed to use a combination of farm waste, municipal solid waste (MSW) and commercial/industrial (C&I) waste streams. The main plants identified included the large AD plant in Holsworthy, Devon (2.7MW); Lowbrook dairy farm AD plant in Blandford Forum, Dorset (0.4MW); Smerill Dairy farm AD plant in Kemble, Cirencester (0.3MW); and the Compact Power pyrolysis/gasification plant in Avonmouth, Bristol (0.2MW).

Table 5-3: Renewable electricity and heat capacity in the South West of England in 2009 (source: DECC, 2010b; Ofgem, 2010; RegenSW, 2010)

Renewable electricity source	Installed capacity (MW)	% of total renewable electricity capacity
Landfill gas	74.76	48.3%
Sewage gas	11.09	7.2%
Advanced treatment of waste	3.37	2.2%
Wind	55.39	35.8%
Hydro	8.87	5.7%
Solar PV	1.35	0.9%
Total	**154.83**	**100.0%**
Renewable heat source	**Installed capacity (MW)**	**% of total renewable heat capacity**
Biomass thermal	29.94	53.7%
Sewage gas thermal	11.33	20.3%
Advanced treatment of waste	0.02	0.0%
Heat pumps	9.1	16.3%
Solar thermal	5.39	9.7%
Total	**55.78**	**100.0%**

5.3.1.2. Renewable heat installations in the South-West of England

Biomass makes up 53.7 per cent of the region's renewable heat capacity (see Table 5-3), with 328 installations in a variety of different settings. These range from military barracks and plant nurseries to primary schools and large houses (see Appendix D). The next stage was to ascertain what type and how much biomass feedstock was being used in each plant. This was a difficult task due to the lack of accurate data available. To estimate the amount of biomass used in each plant, data were obtained from the Biomass Energy Centre (2010) on the usual heat loads for different biomass thermal systems (see Table 5-4). This gives the typical annual energy demand, system size and average feedstock required. Similar data was also derived from BEAT (Environment Agency, 2010) and Elsayed *et al.* (2003), which produced analogous results. These data were applied to each of the biomass thermal plants identified to obtain an estimate of the biomass resource currently used for biomass heating.

Table 5-4: Biomass heating of buildings of different sizes (source: Biomass Energy Centre, 2010)

Building	Annual energy demand (MWh_{th})	System size (kW_{th})	Woodchips required Tonnes/yr (30% m.c.)
Domestic house (12% load)	20	20	5.7
Primary School (17% load)	150	100	33.2
Community building (25% load)	221	100	48.8
Commercial building (25% load)	1,100	500	218.8
Large farm with outbuildings (30% load)	400	150	114
Commercial Greenhouse (40% load)	4,200	1,200	1,200

From these calculations it was estimated that a total of 17,000-20,000 odt are currently used for biomass heating installations (>50kW) in the South West of England. Whilst these figures give an estimate, precise energy requirements for a given building will depend on many constructional and operational factors. It is also very difficult to ascertain the exact biomass sources utilised, therefore some care should be taken when interpreting results.

5.4 BIOMASS RESOURCE ASSESSMENT FOR THE SOUTH WEST

This section follows the methodology set out in Chapter 3 section 3.2. Each feedstock is defined and a brief description given of how the resource was quantified. Different constraints on the available resource are discussed before defining a resource equation for each feedstock and quantifying the total resource.

5.4.1 Agricultural wastes and residues

Given the South West region's large agricultural sector, agricultural wastes and residues were considered to be widely available. This biomass resource was divided into agricultural manures and straw.

5.4.1.1. Agricultural manures

Animal manures arise from the faeces of farm animals such as cattle, pigs, sheep, chickens and horses. Farmyard manures also often contain straw which has been used as bedding for animals. Such manures are more solid and generally referred to as farmyard manure. Farmyard waste also often comes in a liquid form known as slurry, which can be utilised in anaerobic digestion plants. As animal manures are derived from livestock, data was obtained from DEFRA on the total number of cattle (dairy and beef), pigs and poultry (see Table 5-5). Sheep were not included as they spend almost all year outside in the pasture range or paddock, and so it is not practical to collect their manure (DEFRA, 2005). Horses were also excluded as the average number in the South West is 6 horses per holding (DEFRA, 2009), which means the manure arisings are too dispersed. Figure 5-3 summarises the method applied in calculating the animal manure resource:

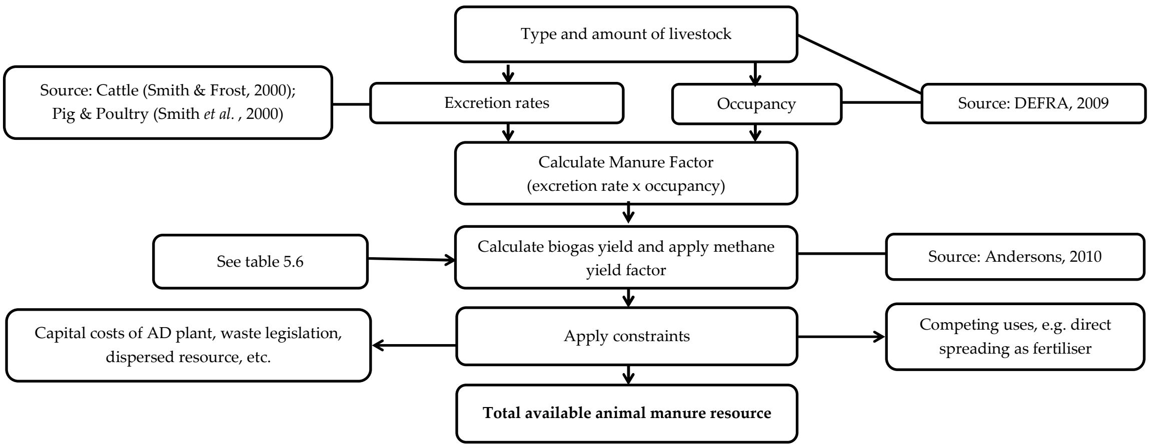


Figure 5-3: Method applied in calculating the available animal manure resource

Each animal category has a different excretion rate, manure dry matter content and farm management system. Excretion rates were taken from (Smith & Frost, 2000) for cattle and (Smith *et al*., 2000) for pigs and poultry. As the weight of cattle can vary an average weight of 550 kg was assumed for dairy cattle and 500 kg for beef cattle. For pigs, an average excretion rate was taken across the different types of pig, and for poultry only laying birds were included as they are known to be housed. Occupancy is the amount of time each type of livestock spends inside (DEFRA, 2009), which gives the collectable resource, since excreta outside are considered uncollectable. Farms which leave their livestock outside for much of the year (like sheep farming) therefore have negligible occupancy. Table 5-5 summarises this information and calculates the manure factor.

Table 5-5: Livestock data – numbers, excretion rates, occupancy and manure factor

Livestock type	Livestock numbers 2007	Excretion rate (tonnes / year)	Occupancy	Manure factor (tonnes / year)
Dairy cattle	760,818	19.2	59%	11.33
Beef cattle	1,042,751	11.7	50%	5.85
Pigs	480,055	1.87	90%	1.68
Poultry	5,952,707	0.041	97%	0.04
Source	DEFRA, 2009	(Smith & Frost, 2000), (Smith *et al.*, 2000)	DEFRA, 2009	Calculated – excretion rate * occupancy

Using Table 5-5 and data on biogas yield per tonne of feedstock allows an average methane yield factor to be calculated. This multiplies the manure factor, biogas yield and the methane content of the biogas. Basic data available for expected biogas yield for each feedstock type are shown in Table 5-6 (Andersons, 2010). It is assumed that the biogas is 60% methane (CH_4) and that the median value is taken as the biogas yield. Total methane yield in the South West can thus be calculated by multiplying the methane yield factors by the livestock data.

Table 5-6: Dry matter content, biogas yield, methane yield and methane yield factor for different livestock slurries

Feedstock	Dry Matter (%)	Biogas yield (m^3/tonne)	Average methane yield (m^3 per tonne per annum)	Average methane yield factor (m^3 per head per annum)
Dairy cattle slurry	10	15 – 25	12	135.9
Beef cattle slurry	10	15 – 25	12	70.2
Pig slurry	8	15 - 25	12	20.2
Poultry slurry	20	30 - 100	39	1.6
Source	Andersons, 2010		Calculated – CH_4 60% and median biogas yield	Calculated – Methane yield * Manure factor

Animal manures have been used for centuries as a fertiliser for farming as it improves the soil adding nutrients and water. DEFRA (2005) shows the current manure and slurry management systems used in the UK for these feedstocks. The main existing use is therefore the direct spreading of slurries and manures onto agricultural land. However, using this resource in anaerobic digestion (AD) improves the quality of the fertiliser by-product. It generally has higher nitrogen content than slurry, kills most pathogens and seeds in the feedstock, thereby killing feedstock borne diseases and preventing the spread of weeds (Andersons, 2010). Hence for this resource assessment it is assumed that all of the calculated animal manure resource is available. As a waste stream the alternative end uses are limited, with those slurries not used as feedstock generally sent to landfill or incinerated (Andersons, 2010). Assuming no constraints the available animal manure resource is calculated as **180,000,000-200,000,000m^3 of CH_4**.

5.4.1.2. Straw

Straw can be defined as an agricultural by-product of cereal and oilseed production. The main sources of straw in the South West are from wheat, barley and oilseed rape, which are grown primarily for their grain for the food market. Straw is the dry stalks of the plants which remain once the primary crop has been removed. On average, grain accounts for 51% of the total above ground biomass of wheat and barley, and 30% for oilseed rape (ADAS, 2008). The availability of straw is affected by a variety of factors. These include the type of crop, amount of crops, straw yields per crop, harvesting methods, alternative uses for straw, and farm management choices. Figure 5-4 shows the methods and data sources for quantifying the availability of straw in the South West.

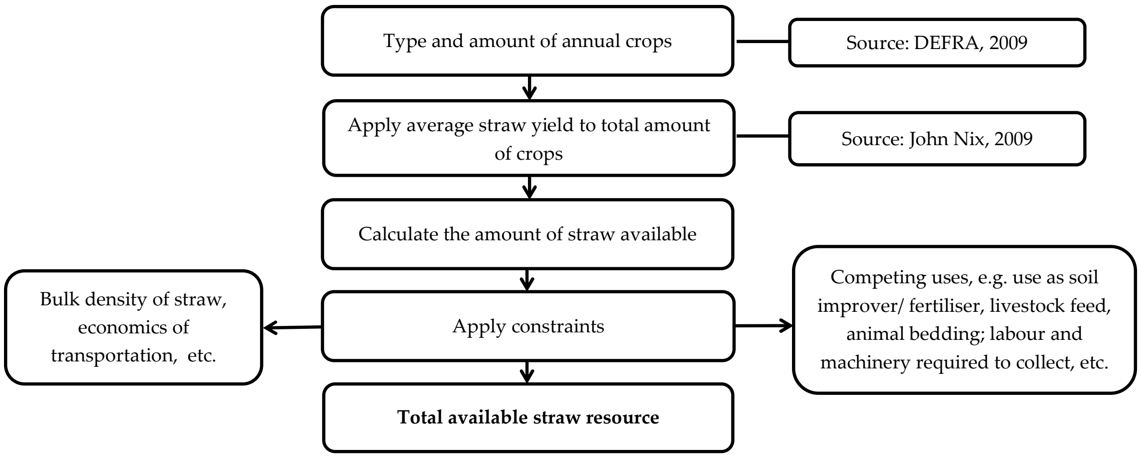


Figure 5-4: Method applied in calculating the available straw resource

The starting point was to establish the type and amount of crops grown in the region. An average crop production from 2000 to 2007 was used to allow for crop rotations, seasonal variations in yield and changing market prices for crops. Due to the height above ground at which the straw is cut and the efficiency of straw balers generally only 60% of straw can be recovered (ADAS, 2008). Straw yields vary depending on a number of factors therefore average yield data were taken from John Nix (2009). Table 5-7 summarises the findings and estimates of the total straw production in the region.

Table 5-7: Straw production in the South West of England

Crop	Average total hectares 2000-2007 (ha)	Average straw yield (tonnes / ha)	Total straw production (tonnes)
Wheat	181,588	3.5	635,558
Barley	109,688	2.75	301,642
Oats	19,207	3.5	67,225
Other cereals	6,537	3.5 [a]	22,880
Oilseed rape	40,095	1.5	60,143
Linseed	9,044	1.5 [b]	13,566
Total			**1,101,013**
Source	DEFRA, 2009	John Nix, 2009	Calculated

a other cereals assumed to have same average straw yield as wheat and oats
b linseed assumed to have same average straw yield as oilseed rape

The above analysis shows that over 1.1m tonnes of straw are produced annually in the South West. This finding is similar to the study of srtraw availability completed by Edwards & Suri (2007). Nevertheless, several alternative and competing uses exist for straw. Most importantly in the South West region is the use of straw for both animal feed and animal bedding. This is apparent given the high amount of livestock farming in the region. Straw is currently fed to livestock as a source of long fibre, an essential part of the cattle and sheep diet, and used for dairy, beef, pig and horse bedding (CSL, 2008). Given the high amount of livestock in the region, the CSL (2008) study estimated that the livestock market demand for straw slightly outweighs straw supply in the region. This implies that straw is not a readily available biomass resource in the South West.

Another important use of straw is ploughing back into the soil to improve soil fertility and structure. It is estimated that 40% of straw is incorporated back into the soil (Nix, 2003). Straw is a valuable source of nutrients which have become increasingly expensive when purchased and applied in inorganic fertiliser form (ADAS, 2008). Consideration must therefore be given to the cost of buying fertilisers in comparison to the nutrient value of straw and the associated costs of straw bailing and removal. CSL (2008) estimated that at current fertiliser prices, a minimum wheat straw value of around £32/tonne is required to persuade most farmers to sell their straw.

Bulk density of straw also affects its availability for bioenergy use. Due to the difficulties associated with transporting straw long distances, it is generally considered uneconomic to transport straw over distances greater than 30 miles (Bioregional, 2003). Similarly, the net energy benefit is greatly reduced when transporting biomass over distances. Much of the straw resource may also be difficult to access, for example, steep slopes or remote fields. Labour and machinery are also required to collect this resource, which is why it is often ploughed back into the field.

These constraints have shown that there are a variety of considerations when assessing the availability of straw. Most importantly at present is the competing use for livestock feed and bedding which at current livestock levels leaves the South West as a net importer of straw. The nutrient value as a fertiliser and carbon sequestration value of straw is also important, as is the economics and practicalities of collection and distribution. Therefore, this resource assessment concludes that no straw is presently available for use in bioenergy systems in the South West.

5.4.2 Energy crops

5.4.2.1. Perennial energy crops

Energy crops can be defined as those plants grown principally for their energy content. The term perennial is given to plants that live for more than two years. Currently in England perennial energy crop growth is supported by the energy crops scheme (ECS). This supports the cultivation of Miscanthus and short rotation coppice, such as Willow, Poplar, etc. There are no annual conventional food crops that are supported. Therefore it is useful to make the distinction between perennial and conventional annual energy crops.

There are currently 1,251 ha of Miscanthus and 39 ha of SRC planted in the South West under the ECS (Natural England, 2010). It is likely that more plantations exist which are not part of the ECS, but these are not included in national statistics. There is also the possibility that some hectares of perennial energy crops may have been removed. Again, this is not recorded in national statistics. These two anomalies are considered to be fairly insignificant and to even each other out. Hence the total current perennial energy crop resource available for bioenergy is easily obtained.

As energy crops are grown specifically for their energy content the main constraints arise from the restrictions of the land available and competition from other crops or investments. Environmental constraints include nitrate vulnerable zones, AONB, national parks, ancient woodland, SSSI, etc. DEFRA has produced a constraints map which highlights such restrictions on growing energy crops (DEFRA, 2007d), other considerations include the local climate, topography, etc (Tuck *et al*., 2006). If sustainable bioenergy production is to be pursued then dedicated energy crops are likely to be grown on existing agricultural land (DEFRA, 2007a; EEA, 2006), this may include some arable land (including that previously under set-aside) and some temporary grassland. In this study other land is considered inappropriate due to potential environmental impacts of land use change.

Yields for Miscanthus and SRC Willow are taken as 12 odt/ha and 8 odt/ha respectively (DEFRA, 2007d). Applying these yields to the current amount of Miscanthus and Willow planted in the South West gives 15,012 odt of Miscanthus and 312 odt of Willow. Therefore the total currently available perennial energy crop resource is approximately **15,324 odt**.

5.4.2.2. Conventional crops

Statistics are maintained by DEFRA on the amount of hectares of each type of conventional annual crop (see Table 5-2). Currently the vast majority of these crops are used for food production, with some used as feed for livestock. The main possible exception to this is oilseed rape as interest has grown in the production of biodiesel. However with the current data available, it is not known what the exact end-use is. Therefore, all current production of cereals and oilseeds are considered to be used in food and animal feed production, and are not currently available as a biomass resource.

5.4.3 Forestry

Forestry comprises of woodfuel sources arising from forests and woodland. This includes forestry residues, stemwood, sawmill co-products and arboricultural arisings. The market for bioenergy in Britain provides an opportunity for the UK's forest industry to receive income from its residues, giving the forest industry a market for its by-products and increasing its competitiveness. Since forestry materials arise as a consequence of other forestry activities, the marginal energy costs and emissions from its production are minimal (RCEP, 2004).

Almost all estimates of the UK forestry and forest residue resource base can be traced back to Forestry Commission statistics and in particular the 2003 report: Woodfuel Resource in Britain. The source data for this report are the National Inventory of Woodland and Trees, a periodic survey undertaken by the UK Forestry Commission (Forestry Commission, 2001), and a database held by the Commission that describes the forested areas they manage. The latest inventory (conducted from 1994 – 2000) can be considered the definitive dataset for estimates of the forested area in the UK (UKERC, 2010). Due to the scope of this resource assessment this dataset is considered the most appropriate from which to calculate the South West forestry resource. Table 5-8 summarises the different types of forest in the region.

Table 5-8: Summary of woodland area by forest type in the South West of England (source: McKay *et al.*, 2003)

Forest Type	No. of hectares
Conifer	48,345
Broad-leafed	120,194
Mixed	30,205
Coppice	1,093
Coppice with stands	805
Felled	1,180
Open space	10,201
Total	**212,023**

Figure 5-5 shows the methods and data sources for quantifying the available forestry resource.

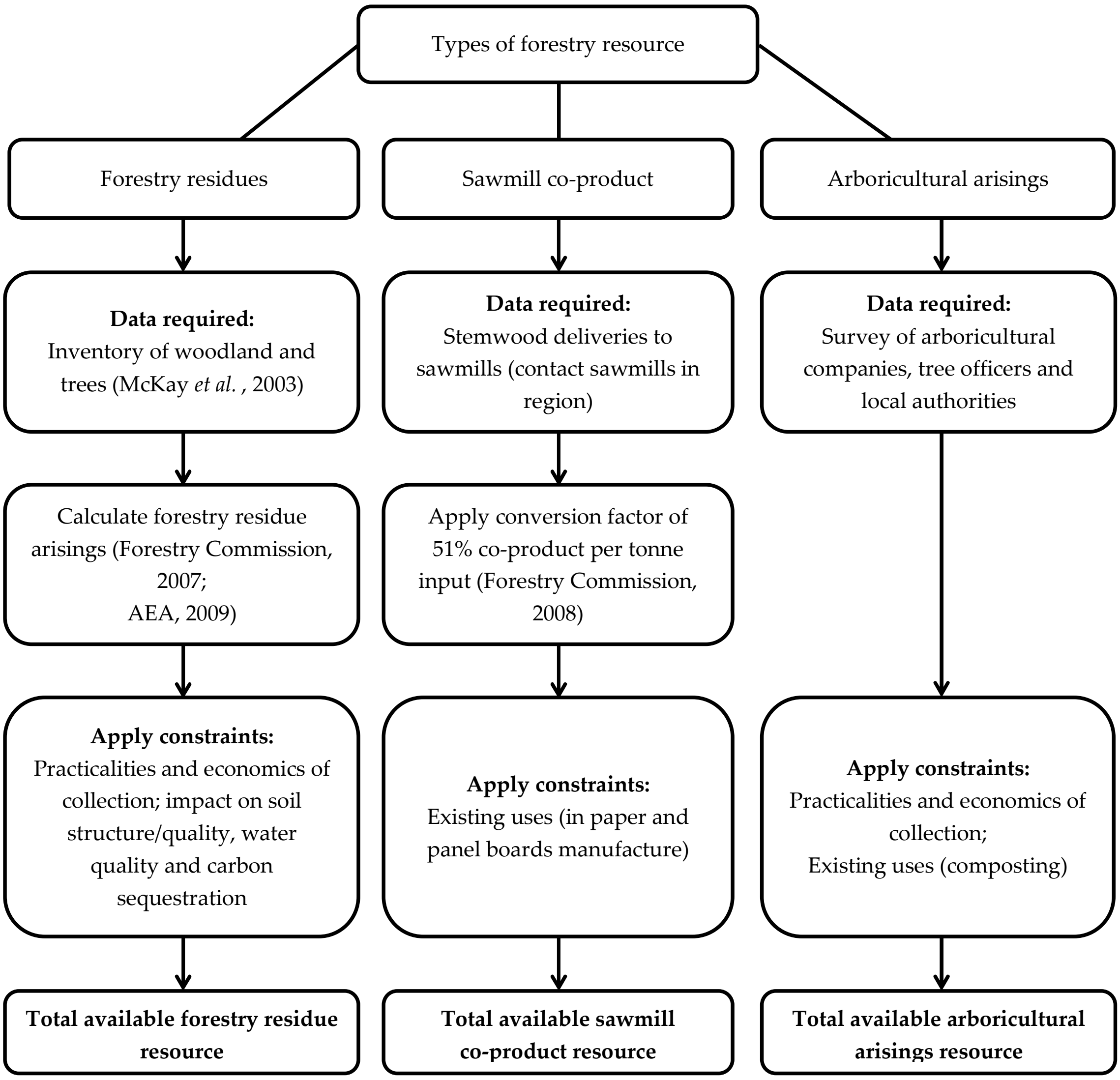


Figure 5-5: Methods applied in calculating the available forestry resource

5.4.3.1. Forestry residues

Forestry residues consist of woodland management arisings, treetops and limbs that result from traditional logging industry activities, excess amount of undergrowth in forests and wood from pest or storm-damaged woodland (RCEP, 2004). McKay *et al.* (2003) describes the potential resource of forestry residues as poor quality stemwood, tips and branches. Utilising the resources from currently under managed woodlands would make a significant contribution to the arisings of forestry residues available for conversion to energy (Forestry Commission, 2007). A potential disadvantage that would need to be accounted for is the negative effect of removing this material from a forest (Lattimore *et al*., 2009). If it were removed in excess this could result in a decline in soil quality and structure, a decline in water quality and a decline in carbon sequestration (IEA, 2010b; Royal Society, 2008).

It was estimated by McKay *et al.* (2003) that there are 125,633 odt of forestry residues currently available in the South West. However the availability of the resource is an issue because it is already marketed to other industries and any remaining residue left on the ground contributes to effective forestry management through decomposition and soil nutrient maintenance (AEA, 2009a). This estimate does also not take into account the economic feasibility of extracting this resource.

The Forestry Commission estimate that, of the total available resource, 10% of the small round-wood and 100% of poor quality stemwood, stem tips and branches could be made available to new wood fuel projects without serious disruption to existing wood-using industries (Forestry Commission, 2007). These percentages were applied to the McKay *et al.* (2003) study to calculate the available forestry residues in the presence of existing industries, which gave a total available biomass resource of **75,000-80,000 odt**. The actual availability is likely to change over time depending on various factors, including financial support, infrastructure and incentives, transportation costs, accessibility, harvesting costs, timber prices, and prices of competing co-product markets (RCEP, 2004).

5.4.3.2. Stemwood

Stemwood is the main product obtained from the harvesting of a tree. It is the wood produced from the stem, i.e. its main axis, as opposed to wood produced from branches, tips or stumps, etc. Due to its high economic value as wood for use in construction and other wood-based industries, stemwood is not considered to be an available biomass resource for the South West.

5.4.3.3. Sawmill co-product

Sawmills processing coniferous logs produce sawn timber, wood chips, sawdust, pin chips, shavings, slab wood and bark (Confor, 2010). Sawmill co-products therefore relate to all the products except sawn timber. The largest consumers of sawmill products are the wood based panel and paper industries. Forestry Commission (2008) statistics define a conversion factor for the ratio of co-product produced for each tonne of stemwood input as 51%. This is an up-to-date and detailed data source which also gives the existing uses of sawmill co-products (Forestry Commission, 2008). By obtaining the number of stemwood deliveries, applying the conversion factor, and subtracting the existing uses (AEA, 2009a), the total sawmill co-product resource in the South West is calculated as **26,000-28,000 odt**.

5.4.3.4. Arboricultural arisings

Arboricultural arisings are defined as material that becomes available as a result of tree surgery in, for example, parks, streets, school grounds and private gardens and from site clearance for building, construction and road developments. These residues are usually left on-site in the form of chippings or removed to landfill, with only a small proportion currently used in energy end markets (AEA, 2009a).

An estimate of the total arboricultural arisings for each region was performed by AEA (2009a). Their study was based on data collected by McKay *et al.* (2003) who used a questionnaire analysis of arboricultural companies, tree officers and local authorities. AEA (2009a) found that in the South West there are currently 34,830 odt produced each year, of which 27,000 odt are not marketed. There are not many competing uses for arboricultural arisings other than composting and energy usage. The economics and practicalities of collection are considered to be the main barriers which prevent a bigger uptake of this resource for energy. Therefore all of the **27,000 odt** is considered to be a readily available biomass resource.

5.4.4 Industrial and domestic wastes and residues

Wastes and residues are generated from a wide variety of industrial sectors and households. Different wastes and residues have been assessed separately, as their composition, availability, location and energy content may be different.

5.4.4.1. Waste wood

Waste wood arises from a wide variety of sources, in varying quantities and levels of purity. There are essentially two main categories, clean (untreated) waste wood and contaminated (treated) wood. Clean waste wood can be used in a wide variety of biomass applications, whilst treated waste wood is regulated under the Waste Incineration Directive (WID) and requires more expensive equipment to prevent the release of harmful emissions (EU, 2006). This reduces the number of uses for treated wood waste. The main sectors from which wood waste arises are construction; demolition; industrial; municipal; and packaging (WRAP, 2009). Construction and industrial waste wood are considered to be clean waste wood, whereas demolition and municipal are contaminated sources. Packaging is not considered to be an available biomass resource as almost all of this resource is recycled into particle board (WRAP, 2009).

Several studies were reviewed to assess the current available waste wood resource available. These included Confor (2010); WRAP (2009); AEA (2009a); DEFRA (2008b). It was found that the WRAP (2009) study provided the most up to date data from the main sectors identified, which was also broken down into regional estimates. In their study both a top down and a bottom up approach were used, key industry stakeholders were interviewed and over 300 companies were surveyed (WRAP, 2009). The sources of waste wood from each sector are summarised in Table 5-9, this shows the main sources of wood waste arise from packaging, demolition and construction. Arisings in the South West are smaller than the areas of higher population density such as in the South East (626k odt), North West (543k odt) and London (535k odt).

Table 5-9: Wood waste stream by sector for the South West (source: WRAP, 2009)

Sector	Wood waste	Assumed use by panel industry	Assumed use for animal bedding	Estimated available biomass resource
		(thousand tonnes)		
Construction	96.4	32 (33%)	26 (27%)	38.4
Demolition	101.2	33 (33%)	27 (27%)	41.2
Industrial	41.9	14 (33%)	11 (27%)	16.9
Municipal	69.1	23 (33%)	19 (27%)	27.1
Packaging	106	106 (100%)	0 (0%)	-
Total wood waste	**414.6**	**208 (50% of total)**	**83 (20% of total)**	**124 (30% of total)**

Although wood waste does offer a good potential resource, consideration must be given to its current existing uses. For well over a decade the wood based panel industry in the UK has utilised recycled wood waste, with over 50% of the available resource used to make particle board (Confor, 2010). The latest demand data obtained showed that 58% of wood waste is consumed by the wood panel board manufacturers; however this demand is predicted to fall over time as the industry's output is falling (WRAP, 2009). For this resource assessment it is assumed that 50% of the available resource is consumed for panel boards. Of this 50%, all of the packaging wood waste is assumed to go to this use, with one third of the resource from each of the other sectors, i.e. 208 thousand tonnes in total.

Biomass energy generation is considered to be the second most important existing use for waste wood. Current demand is estimated to be around 25%, but this is expected to increase over time with the demand for panel board decreasing (WRAP, 2009). The third most important end user industry of waste wood is the production of animal bedding, which accounts for around 20% of demand and is expected to remain relatively constant over time (WRAP, 2009). Bedding made from wood waste is predominantly used to keep chickens and other poultry (DEFRA, 2008b). From the above analysis it is estimated that **55,300 odt of clean wood waste** (from construction and industry) and **68,300 odt of contaminated wood waste** (from demolition and municipal) are currently available for biomass energy production.

5.4.4.2. Sewage sludge

Sewage sludge refers to the residual, semi-solid material left over from industrial wastewater or sewage treatment processes. Sewage treatment works represent a direct source for collection of sewage waste from which the sludge component can be used to generate biogas through Anaerobic Digestion. This pathway for biomass energy is already being utilised in several places across the region.

Data on the current production of electricity from sewage sludge was obtained from DECC (2010b). In addition, Ofgem maintain data on all renewable electricity production generated for the ROCs. This data gives the total amount of electricity generated in MWh_e and not the actual physical biomass resource. To obtain this data it is necessary to use the Environment Agency's database of sewage treatment works to provide the volumes of effluent discharged. Data on the discharge level is also available via company returns submitted to OFWAT. Having reviewed this data, each of the three water companies in the South West region were contacted. This established that at present none of the companies were planning to develop further sewage sludge plants, primarily due to the capital costs involved (D. Green, Sustainability planning manager, Wessex Water, 2011, personal communication). Therefore, the present utilisation of sewage sludge was considered to be the total amount currently available.

Ofgem have details of all sewage gas digestion plants in the UK. It was found that in total there is 11MW of installed capacity in the South West from 16 sewage treatment works, which means the South West has 6% of the UK total (Ofgem, 2010). This percentage was applied to the DECC (2010b) statistics to calculate the amount of sewage sludge presently utilised. This gave the total amount of sewage sludge and subsequent electricity generated in the UK. From this it was estimated that 38GWh of electricity is generated using **17-18M m^3 of CH_4 from sewage sludge** biogas in the South West.

5.4.4.3. Municipal solid waste (MSW)

Municipal Solid Waste (MSW) is waste from household kerbside collections, civic amenity sites and other collected wastes. It contains food waste which is normally mixed with a variety of other waste components. Food waste can be used as a feedstock for anaerobic digestion. Other waste streams were considered less suitable for bioenergy, with the exception of wood waste which is assessed above. DEFRA maintain statistics on the total food waste resource collected in their Waste Data Flow (WDF) dataset. This contains waste returns at waste disposal authority level. In 2009, the total municipal waste collected in the South West was 2,824 thousand tonnes, and the proportion of food waste in the waste stream was 20% (DEFRA, 2010b). This gives the total amount of food waste collected in the South West region in 2008/09 as 564.8 thousand tonnes.

MSW is a very abundant biomass resource but its actual use in energy applications is restricted because it can be difficult to separate out the organic food component from other household waste. Some local authorities in the region already have food waste collections, such as B&NES and Bristol City councils, whereas the local authority of Wiltshire does not. In more rural parts of the region separate food waste collections can be very expensive due to the dispersed nature of this resource. MSW is therefore more readily available in densely populated urban areas. Over the longer term it is debatable how the MSW resource availability will evolve. It is assumed that the amount of waste generated will remain relatively constant, but more food waste should become available as source separation becomes more common.

Only food waste has been included in this resource assessment as other waste streams are either dealt with in other sections, are not biomass sources, or are difficult to separate from other waste streams. For this study it has been assumed that 50% of the available resource can be separated from the MSW waste stream, giving the total food waste arisings available as 282.4 thousand tonnes. The methane yield from this resource can be calculated by using an average methane yield factor for food waste, obtained from BEAT, was 86m^3/t (Environment Agency, 2010). This gives the total currently available biomass resource from municipal food waste as **24-25M m^3 of CH_4**

5.4.4.4. Commercial and industrial waste streams

Commercial and industrial (C&I) waste is controlled waste arising from the business sector. Commercial waste is waste arising from the activities of wholesalers, catering establishments, shops and offices. Industrial waste is waste generated by factories and industrial plants. There is no statutory requirement for businesses to provide data on the wastes they produce, so previous studies are important in estimating the amount in this waste stream. A study by AEA (2009a) identified the main types of C&I waste and the likely composition of the waste stream. The data used in the AEA study is derived from DEFRA and Environment Agency waste data. Total arisings for the South West in 2002/03 were 2,967 thousand tonnes of commercial waste and 2,589 thousand tonnes of industrial waste (AEA, 2009a). Nevertheless much of this waste is either recycled or unsuitable for energy applications.

The most comprehensive and up to date study on C&I waste was undertaken by ADAS (2009). In this study, data on the waste arisings were calculated based on the number of companies in each standard industrial classification (SIC) sector for each region. This gave amounts for each sector by company size and material type by sector. ADAS (2009) estimate that in total there were 4,760,250 tonnes of C&I waste produced in 2006/07, which is slightly less than the AEA study. Only some of this waste is suitable for use in bioenergy applications. Table 5-10 summarises the main sectors food waste arisings (taken from ADAS, 2009), estimated recycling percentages (taken from AEA, 2009a), and hence the amount available for biomass energy production:

Table 5-10: Biomass available from Commercial and Industrial Food Waste in the South West of England (source: ADAS, 2009; AEA, 2009a)

SIC Sector	Total food waste (tonnes)	Recycling rates (%)	Total available biomass (tonnes)
Commercial			
Retail & wholesale	150,503	35	97,827
Other services	53,795	35	34,967
Public sector	67,778	35	44,056
Industrial			
Food, drink and tobacco	370,834	45	203,959
Textiles/wood/paper/publishing	7,421	45	4,082
Chemical/non-metallic minerals	2,849	45	1,567
Machinery & equipment	4,847	45	2,666
Total	**658,027**		**389,122**

As with MSW, it is assumed that 50% of the available resource can be obtained which gives 195 thousand tonnes. The methane yield is also assumed to be the same as MSW with 86m^3/t (Environment Agency, 2010). This gives the total currently available biomass resource from C&I food waste as **16-17M m^3 of CH_4**.

5.4.4.5. Landfill gas

Landfill gas is a mixture comprising mainly methane and carbon dioxide, formed when biodegradable wastes break down within a landfill as a result of anaerobic microbiological action. This biogas can be collected by drilling wells into the waste and extracting it as it is formed. It can then be used in an engine or turbine for power generation, or used to provide heat for industrial processes situated near the landfill site. Landfill sites can generate commercial quantities of landfill gas for up to 30 years after wastes have been deposited (REA, 2009). It is difficult to predict how the availability of landfill gas will change over time. Several factors will affect this, but most importantly is the EU and UK Government policies which aim to reduce the amount of waste sent to landfill (EU, 2006).

Data on the current use of landfill gas for energy purposes can be obtained from DECC (2010b). In 2008 there were 4,757GWh of electricity produced from landfill gas in the UK (DECC, 2010b). However, this electricity generation data is not available on a regional level. Therefore an estimate was made based on data obtained on the installed capacity in the region compared to the UK as a whole. Ofgem have details of all landfill gas plants in the UK. It was found that in total there are 54.5MW of installed capacity in the South West from 21 landfill sites (Ofgem, 2010). In comparison the total installed capacity in the UK is 943.7MW, which means the South West has 6% of the UK total (Ofgem, 2010). If this is applied to the national total, then approximately 275GWh of electricity is produced from landfill gas in the South West, i.e. 6% of 4,757GWh (DECC, 2010b). This is an approximation but gives a useful indication of the renewable energy produced from landfill gas.

To derive the amount of methane utilised to produce this electricity, the 6% total was applied to the UK total landfill gas, i.e. 6% of 1,624 thousand tonnes of oil equivalent. Using the DUKES conversion factor of 1 tonne oil equivalent equals 41.9TJ (DECC, 2010b) and the net calorific value (NCV) of methane as 35.8MJ/m^3 (British Standards Institution, 2005) gives **100-105M m^3 of CH_4 from landfill gas**.

5.4.4.6. Waste oils and fats

Waste oils and fats are also utilised for bioenergy, particularly bio-diesel. However oils and fats are dispersed and location specific, making this resource very difficult to quantify. It was therefore decided to extrapolate data from a Supergen Bioenergy resource assessment to estimate this resource for the South West (Supergen, 2008). The population of the South West (~5m) was used to estimate the percentage (~8%) of the total UK waste vegetable oil (75,000t). This gave approximately 6,000t of waste vegetable oil, which is equivalent to 222,000GJ, based on a NCV of 37GJ/t (Elsayed *et al.*, 2003).

5.4.5 Define Resource Equations

To calculate the available resource for each biomass type a resource equation was established. For each resource equation the notation is different, with the exception of the following notation: A = Availability, E = Existing uses

Animal manure resource = **[LiMfiyi – E] x A** **(Eq. 5.1)**

Where Li = livestock numbers, Mfi = manure factor, yi = methane yield for livestock type i

Straw resource = **[Ciyi – E] x A** **(Eq. 5.2)**

Where Ci = crop production, yi = straw yield for crop type i

Energy crop resource = **[(aa – c) + (pa – c)] yi x A** **(Eq. 5.3)**

Where aa = arable area, c = constraints, pa = pasture area, yi = crop yield for crop type i

Forestry residue resource = **[0.1sr + (pqs + t + b)] x A** **(Eq. 5.4)**

Where sr = small roundwood, pqs = poor quality stemwood, t = tips, b = branches

Stemwood resource = **[hs – E] x A** **(Eq. 5.5)**

Where hs = harvested stemwood

Sawmill co-product resource = **[sd x cf – E] x A** **(Eq. 5.6)**

Where sd = stemwood deliveries, cf = conversion factor

Arboricultural arisings resource = **[tsa – E] x A** **(Eq. 5.7)**

Where tsa = tree surgery arisings

Wood waste resource = **[x_w^G – E – R] x A** **(Eq. 5.8)**

Where x_w = MSW+C&I+C&D arisings, G = growth rates, R = recycling

Sewage sludge resource = **sa x A** **(Eq. 5.9)**

Where sa = sludge arisings

MSW resource = **[x_m^G – R] x A** **(Eq. 5.10)**

Where x_m = MSW arisings, G = growth rates, R = recycling

C&I waste resource = **[x_c^G – R] x A** **(Eq. 5.11)**

Where x_c = C&I arisings, G = growth rates, R = recycling

Landfill gas resource = **lg x ed** **(Eq. 5.12)**

Where lg = current landfill gas production, ed = exponential decay

5.4.6 Summary of biomass resource currently available

In sections 5.4.1 to 5.4.4 a variety of data sources were used; different calculations and assumptions were made to quantify the biomass resource in the South West of England which could be made available for bioenergy production. A summary of the amounts of each biomass type quantified is displayed in Table 5-11.

Table 5-11: Biomass resource quantified (by type) as currently available in the South West of England for energy purposes (in m^3 of CH_4 or odt)

Biomass resource group	Biomass resource type	Resource identified as currently available
Agricultural wastes and residues	Animal manures	180-200M m^3 of CH_4
	Straw	None
Energy crops	Perennial energy crops	15,324 odt
	Conventional crops	None
Forestry	Forestry residues	75,000-80,000 odt
	Stemwood	None
	Sawmill co-products	26,000-28,000 odt
	Arboricultural arisings	27,000 odt
Industrial and domestic wastes and residues	Waste wood (clean)	55,300 odt
	Waste wood (contaminated)	68,300 odt
	Sewage sludge	17-18M m^3 of CH_4
	Municipal solid waste (MSW)	24-25M m^3 of CH_4
	Commercial and industrial (C&I)	16-17M m^3 of CH_4
	Landfill gas	100-105M m^3 of CH_4
	Waste fats and oils	6,000t

5.4.7 Primary energy content of the biomass resource

Having identified the biomass resource currently available in the South West, next the primary energy content was quantified. This is achieved by obtaining the net calorific value (NCV) of each feedstock. For the feedstocks which were quantified in terms of methane content (CH_4), a NCV of 35.8MJ/m^3 has been used (British Standards Institute, 2005). For the woody-based biomass the Phyliss database was used (ECN, 2009). Due to the different NCVs of the feedstocks Miscanthus and SRC Willow have been displayed separately, whilst forestry was grouped together. Figure 5-6 summarises the calculated primary energy content (expressed in GJ_{NCV}) for each biomass resource type.

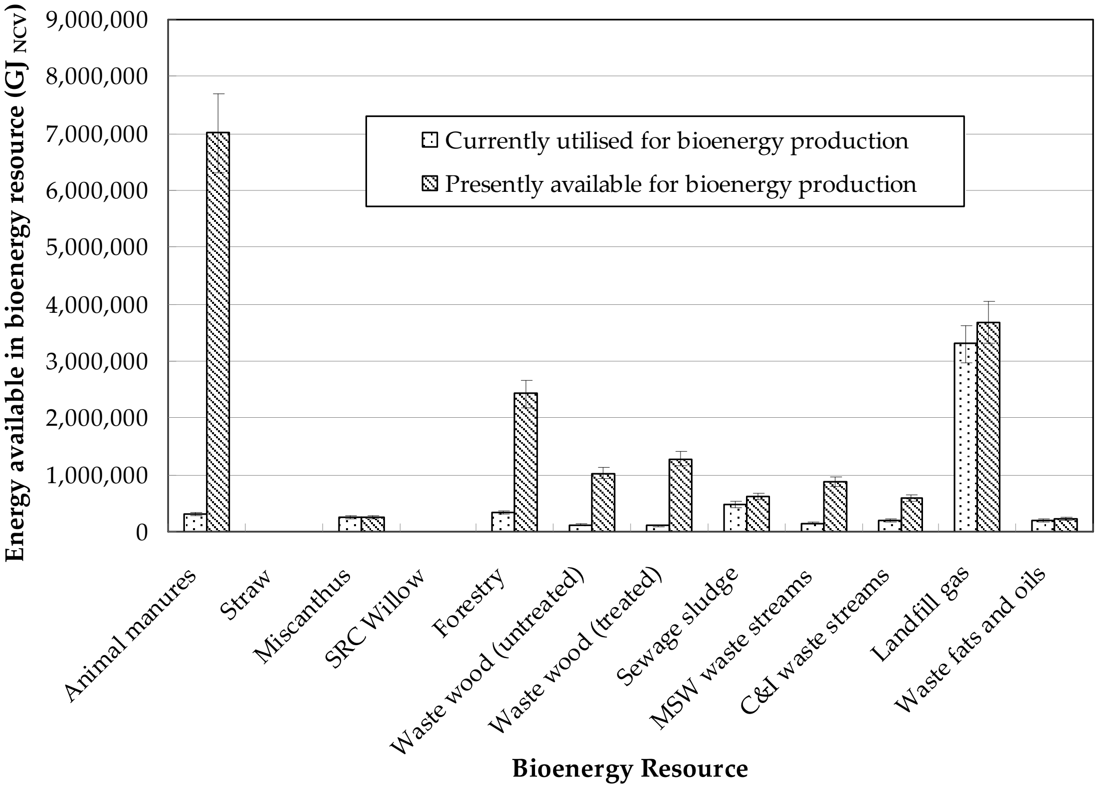


Figure 5-6: Primary energy content of the calculated presently available and currently utilised bioenergy resource in the South West of England

It is therefore apparent that biomass resource is very diverse and has the current potential to utilise 16-20PJ_{NCV} of primary energy. These analyses assume maximum possible energy output available based on the feedstock calorific values. Each calculated value for the biomass resources has a related error value between which the primary energy output can diverge. These deviations are displayed in Figure 5-6 and take account of the differing assumptions on NCV, availability, and the constraints applied.

5.5 IDENTIFY AND ESTIMATE POTENTIAL END-USES

5.5.1 Potential energy generation from biomass resource

Some basic calculations are now provided to give an indication of the potential energy which could be generated from this resource. This is included as it is important to distinguish between primary energy content and the 'delivered' net energy contribution for the biomass resource.

These end-use examples are provided for illustrative purposes only and are estimates of the potential energy generation.

To calculate the delivered energy, the feedstocks were grouped together into 3 categories:

- biogas sources – i.e. those feedstocks quantified in terms of methane content;
- woody biomass (untreated) sources – i.e. forestry, Miscanthus, SRC Willow and clean waste wood, quantified in odt;
- woody biomass (treated) sources – i.e. contaminated wood waste, quantified in odt.

5.5.1.1. Biogas sources

For biogas sources, it is assumed that an anaerobic digestion (AD) process will be used to produce biogas. This is a proven and commercially attractive way to utilise the methane to generate heat or electricity, or both. In reality the biogas composition would vary for each waste stream depending on the composition of the feedstock and AD operating conditions. However, the primary energy content has been calculated based on the amount of methane generated which is the main energetic gas in the biogas. As these feedstocks have relatively high moisture contents, AD is the most suitable conversion route to produce bioenergy. The potential end-uses of biogas could be electricity-only, heat-only or CHP.

To calculate the potential energy generation from biogas 3 different end-uses have been assumed. Firstly, heat-only is produced using a gas boiler (85% thermal efficiency); secondly, electricity-only is produced using a gas engine (35% electrical efficiency); thirdly, CHP is produced using a gas engine CHP unit (35% electrical and 50% thermal efficiency).

5.5.1.2. Woody biomass (untreated)

Untreated woody biomass could be used in a number of different ways to produce bioenergy depending on the desired end-use. Currently in the UK there are very few examples of using wood to generate electricity, except for co-firing. Therefore, the most likely end-use for untreated woody biomass is likely to be heating. Nonetheless wood can be used to produce electricity and CHP; examples included using an organic rankine cycle engine to convert heat into electricity; burning wood in a steam engine; or gasification.

To calculate the energy potential for woody biomass, a wood-chip boiler has been assumed for heat-only (85% thermal efficiency); and a gasification process is used for electricity-only and CHP. To convert the woody biomass into a wood gas (also known as producer gas), the efficiency of conversion is assumed to be 75% (see Chapter 7), as some of the CV of the fuel is lost in converting the solid biomass into a gaseous form. The wood gas can then be utilised in a gas engine or CHP unit in a similar manner to that of biogas produced through AD. For the simple purposes of this resource assessment, the same efficiencies are assumed as for biogas sources.

5.5.1.3. Woody biomass (treated)

Treated wood can only be burnt in Waste Incineration Directive (WID) complaint installations (EU, 2006), which restricts the end-use. WID installations are likely to be of large scale for economic reasons; hence they will be electricity-only or CHP (Bioregional, 2008). Additionally there is unlikely to be sufficient heat demand. For the resource assessment it was considered adequate to assume the same gasification process as for untreated woody biomass.

5.5.1.4. Potential bioenergy production from the current biomass resource

By taking the primary energy content calculated in section 5.4, and applying the assumptions for bioenergy production outlined above, the potential bioenergy production was calculated. This gave three different scenarios for heat-only, electricity-only, and CHP; the results are displayed in Table 5-12.

Table 5-12: Potential bioenergy production from the current biomass resource in the South West of England

Biomass category	Primary Energy Content (PJ_{NCV})	Heat-only (GWh_{th})	Electricity-only (GWh_e)	CHP (GWh_{th})	CHP (GWh_e)
Biogas sources	11-13	2,597-3,069	1,069-1,264	1,528-1806	1,069-1,264
Woody biomass (untreated)	4-5	944-1,181	292-365	417-521	292-365
Woody biomass (treated)	1-2	n/a	73-146	104-208	73-146
Total	**16-20**	**3,542-4,250**	**1,434-1,774**	**2,049-2,535**	**1,434-1,774**

This analysis shows that the currently available biomass resource has the potential to make a positive contribution to the South West region's energy supply. It is useful to display the range of different energy end-uses to highlight the different bioenergy potential for heat, electricity or CHP. Table 5-12 displays the potential energy generation if all of the available feedstocks were utilised for either heat or electricity or CHP. However, in reality a mix of all three is the most likely scenario. These results do not take into account the quality, or "exergy" of the energy produced.

5.5.2 Total energy consumption in the South West of England

In order to put current bioenergy production in context, it was considered useful to present some information on total energy consumption in the South West. DECC publishes annual regional energy consumption data which is divided into domestic, industry and transport consumption (see Table 5-13). These sub-national energy consumption figures are based on final consumption ('delivered energy') and not on primary energy, for example the gas and electricity consumption figures are aggregated from meter point consumption readings (Laura Williams, Statistician, DECC, May 2010, personal communication).

Table 5-13: South West delivered energy consumption (2007) for heat & power by fuel source (Source: DECC, 2010b)

Heat & power fuel source	GWh
Natural gas	41,052
Electricity	26,267
Petroleum products	15,838
Coal	1,459
Manufactured fuels	58
Renewables & waste	644
Total	**85,319**

Table 5-13 shows the final energy consumption for each fuel source, based on the end consumption point. This can also be split into the consuming sector as Industry and Commercial (41,674GWh) and Domestic (43,644GWh). There is also a total of 45,601GWh consumed for transport. In sections 5.3 and 5.4 it was shown that approximately 350GWh of electricity are produced at present in the South West from biomass sources, representing just over 1% of the total electricity consumption in the region. The analysis performed above shows that between 1,434-1,774GWh$_e$ could be produced using all of the currently available resource for electricity production, representing a near 5-fold increase. This could supply 5-7% of the South West's electricity demand.

If the biomass resource was used for heat only, then between 3,542-4,250GWh$_{th}$ could be produced, increasing the biomass heating supply by at least 10-fold. Where biomass heating is utilised this most likely replaces natural gas, petroleum products and coal, and could therefore supply 6-7% of the South West's heating demand.

CHP represents the best use of the currently underutilised biomass resource in terms of both energy and exergy. Utilising the available resource for CHP would produce 1,434-1,774GWh$_e$ of electricity along with 2,049-2,535GWh$_{th}$, which could supply both 5-7% of the electricity demand and 3.5-4.5% of the heat demand in the South West. Or in other words it is estimated that using the potentially available biomass resource for CHP could provide 4-5% of the region's total electricity and heat demand.

5.6 FUTURE POTENTIAL BIOMASS RESOURCE

This section provides an overview of how the availability of each biomass source may evolve over time. Due to the uncertainties associated with predicting the future resource, a qualitative assessment is undertaken.

5.6.1 Agricultural wastes and residues

5.6.1.1. Animal manures

Assuming there is no change in livestock numbers, the resource identified in section 5.4.1.1 would remain relatively constant. It is not anticipated that livestock numbers will deviate much over the next decade and beyond. However, there has been a general decline in livestock due to low and even negative margins (ADAS, 2008). Nevertheless the South West region's geography favours livestock farming due to its steep terrain, permanent grassland and rough grazing land (see section 5.2.4.2). Therefore, for this resource assessment it is predicted that the future animal manure resource is the same as that currently available, i.e. ~7 PJ$_{NCV}$.

5.6.1.2. Straw

The availability of straw in the South West is closely related to the amount of both arable and livestock farming. If the amount of livestock were to decrease then the demand for straw may also decrease. This could also increase the amount of land available for crops which would increase the supply of straw. Other options for increasing the supply of straw available are to use former set-aside land or temporary grassland. However, for this resource assessment it is assumed that both livestock numbers and food crop production will remain fairly consistent. This implies that for the South West straw is not an abundant biomass resource.

5.6.2 Perennial Energy crops

Both Miscanthus and short rotation coppice offer the biggest potential for increasing the current biomass resource base. The current uptake of these crops is low, yet several studies have anticipated a relatively large increase in their production. Various estimates have been completed which attempt to quantify the future amounts of energy crops in both the UK and in Europe. Two studies undertaken by the European Environment Agency (EEA) suggest that the uptake of perennial energy crops in the UK will increase significantly up to 2020 and further still by 2030 (EEA, 2006; EEA, 2007). These studies indicate that perennial crops will play a key role in increasing the biomass supply, if sustainable agricultural practices are pursued.

The main factors driving the increase in bioenergy potential are productivity increases and the assumed liberalisation of the agricultural sector, which results in additional area available for dedicated bioenergy farming (EEA, 2006). Furthermore, with an increase in carbon prices together with high fossil fuel prices, bioenergy feedstock becomes competitive over time compared with traditional wood industries or food crops. The EEA (2006) study made some value judgments which limit the available potential, including some strict environmental assumptions and the assumption that bioenergy crops should not be grown at the expense of food crops for domestic food supply. Overall, the results of these studies can be seen as a conservative estimate of the technically available environmentally compatible bioenergy potential in Europe. However, these are theoretical assessments and the actual uptake will depend on how individual farmers choose to use their land (see Chapter 10).

UK wide studies include the Biomass Strategy which suggested up to 350,000 ha could be used for perennial energy crops in the UK by 2020 (DEFRA, 2007a). Since the South West has approximately 10% of the UK agricultural land (see Table 5-2), this implies that around 35,000 ha could be made available for energy crops in the region. This figure could be higher, given the region's favourable climate for energy crop growth.

Recent studies in the UK by the TSEC-BIOSYS and RELU-BIOMASS projects investigated the potential for different bioenergy crops in the UK. Their studies engaged spatial analysis to identify the environmental capacity for producing Miscanthus and SRC using Willow and Poplar in England. This took the unconstrained resource and the possible location constraints on cultivation. Their general conclusions were that if specific assumptions were made, it would be possible to plant up 350,000ha without significantly reducing current food production or causing the loss of threatened habitats. To achieve the 1Mha needed to meet both the 15 per cent renewables target and the 10 per cent biofuel directive may also be achievable, but would be much more demanding (Lovett *et al.*, 2009). Variation in productivity was identified due to a range of factors, including genetics (Aylott *et al.*, 2008) and hydrology (Richter *et al.*, 2008). One of the conclusions was that different bioenergy crops should be employed in different parts of the country, otherwise the projected yields could not be delivered.

There have also been some studies that have focused on the South West. Scholes (1998) estimated the maximum resource potential for SRC Willow as 2,794,770 odt and for Miscanthus as 4,546,650 odt, which implies an energy potential of ~51PJ_{NCV} from SRC Willow or ~81PJ_{NCV} from Miscanthus. This assumes a 20% uptake of available arable land and very high yields, therefore the Scholes (1998) estimate is not considered to be realistic. Capener *et al.* (2005) estimated >200PJ_{NCV} could be made available which is even less realsitic. Hammond *et al.* (2008) estimated 57,000ha of land could be used in the South West for Miscanthus production, yielding approximately 8PJ_{NCV} of primary energy.

Before being abolished in 2008, set aside accounted for 2.5% of the total farmed agricultural land available in the region corresponding to approximately 46,340 ha of land (DEFRA, 2009). Other land which could be suitable for energy crop production is temporary grassland (ADAS, 2008; Hammond *et al*., 2008a). Table 5-2 showed that this accounts for over 200,000 ha, or 4 times the amount of land allocated for set-aside in 2007. It is estimated that only 40% of set-aside land and bare fallow would be used by farmers, leaving the rest uncropped (Hammond *et al*., 2008b).

By eliminating set-aside and increasing the use of temporary grassland, the amount of land available for energy crops would increase. This offers farmers an alternative income, allowing the production of energy crops alongside the existing food and feed crops. However, the relative returns available to farmers will affect the actual uptake of energy crops (see Chapter 4). Hammond *et al.* (2008b) suggest that 57,000 ha could be used to grow energy crops, accounting for 2.7% of the region's farm land. This is not considered to have serious impacts on food production as between 2002 and 2006 the total farmed area increased by 112,000 ha (DEFRA, 2009; Hammond *et al*., 2008b).

If the economic barriers to increasing perennial energy crop supply can be overcome (as analysed in Chapter 4), then it is likely the land availability barrier will also be reduced. Given the apparent higher profitability of Miscanthus it seems reasonable to assume that the vast majority of the area would go into Miscanthus production. Also Miscanthus is more suited and higher yielding in the South West than SRC Willow (DEFRA, 2007d). If it is assumed that the arable farming industry is equipped in terms of staff and machinery to be able to actively farm 95% of the total arable area due to restructuring during the set-aside years, then it is possible that 5% of the arable area (~24,000 ha) could be put into dedicated energy cropping (ADAS, 2008). Hence for this resource assessment it is estimated that the uptake of Miscanthus could be between 24,000 ha and 57,000 ha. This could result in an additional 288,000 odt (~5PJ_{NCV}) up to 684,000 odt (~12PJ_{NCV}) of Miscanthus per annum.

5.6.3 Forestry

Forests take time to establish and therefore it is not anticipated that the forestry biomass resource will increase notably over the next decade and beyond. Predictions from Forestry Commission (2010) indicate little or no increase in available woodfuel biomass until 2021. Therefore, for this resource assessment it is predicted that the future forestry resource is the same as that currently available, i.e. ~2.5PJ_{NCV}.

5.6.4 Industrial and domestic wastes and residues

Over the past several years DEFRA and the Environmental Agency have informed waste management legislation to encourage the application of the waste hierarchy. This encourages waste minimisation, reuse and recycling ahead of energy recovery. Various policies have also been implemented such as landfill tax, packaging regulations, Waste and Emissions Trading Act (DEFRA, 2007c). Therefore the availability of waste streams cannot be expected to increase over time.

Waste streams could potentially decrease over time due to increased recycling and stringent regulations on landfill sites. Indeed, in 2004 a regional waste strategy was introduced for the South West with the aim being to become a minimal waste producer by 2020 (South West Regional Assembly, 2004). However, using wastes and residues for energy purposes will also become more economically attractive as waste management companies can generate a gate fee and income from energy production. The assumption for this resource assessment is that the waste resource available for bioenergy production will remain similar. As landfill reduces, so the uptake of anaerobic digestion for wastes and residues will increase.

5.7 SUMMARY

This chapter has outlined a range of data collection methods needed to carry out a detailed resource assessment. The total currently available biomass resource in the South West has been calculated as 16-20PJ_{NCV} in total. This is broken down as 11-13PJ_{NCV} of biogas based sources arising from agricultural, domestic and industrial organic wastes; 4-5PJ_{NCV} of clean wood based sources arising from perennial energy crops, forestry and industrial waste wood; and 1-2PJ_{NCV} of contaminated wood based sources arising from demolition and municipal waste wood. An additional step carried out was to estimate the potential energy generation which could be realised if this current resource was maximised for bioenergy utilisation. This showed that biomass from the region could generate 4-5% of the total heat and electricity demand in the South West if used in CHP applications, which represents a significant increase from current bioenergy production in the region.

It has been demonstrated that the bioenergy potential for the South West is good. There are a number of under utilised existing biomass resources which could be used for bioenergy production. Due to the large agricultural sector in the region the biggest potential unutilised current resource arises from animal manures and slurries. Increasing the use of waste and the woodland resource will also favour an increase in bioenergy production without much impact on current land use, existing industry and supply chains. To achieve the maximum current bioenergy potential a wide range of constraints will need to be overcome as highlighted in this chapter. Perhaps most important is the practicalities and economics of cultivating, collecting and using the biomass resource for energy purposes.

In addition to maximising the use of the current biomass resource, there is also the scope to increase the future biomass supply. For a much wider uptake of bioenergy, energy crops could be grown more widely. This has implications for land use change, commodity prices, the environment, etc. It was estimated that an additional 5-12PJ_{NCV} of primary energy supply may become available in the South West if between 24,000 ha and 57,000 ha of agricultural land are used to grow perennial energy crops. The next chapter undertakes a life cycle assessment of both Miscanthus and SRC Willow to assess the potential environmental impacts of an increase in these crops.

CHAPTER 6. LIFE CYCLE ASSESSMENT OF PERRENIAL ENERGY CROPS

This chapter applies life cycle assessment (LCA) methodology described in Chapter 3 to the production of the perennial energy crops Miscanthus and Willow. These crops were selected as they are the primary crops being grown in England under the Energy Crops Scheme (Natural England, 2009a) and were identified in Chapter 5 as potentially playing an important role in increasing the current biomass resource base. A review of the literature in Chapter 2 revealed that there have been several net energy and greenhouse gas studies performed on SRC Willow, with fewer performed on Miscanthus. However there are very limited numbers of environmental LCA studies undertaken on these crops. Therefore this work provides an important contribution due to the detailed life cycle inventory compiled and the subsequent analysis of potential impacts provided in the impact assessment. The findings from this chapter were presented at the 1st SETAC Young Environmental Scientists conference held at the University of Landau, Germany in March 2009.

6.1 GOAL AND SCOPE

This LCA was performed to assess the potential environmental burdens of the production of perennial energy crops. The goal is to complete a life cycle inventory (LCI) and impact assessment of the energy crops Miscanthus and SRC Willow. Data for the LCI have been collected based on the energy and material inputs and outputs required to cultivate one hectare of arable land. Perennial crops remain in ground for several growing seasons, so it is necessary that the LCI includes all inputs and outputs per hectare over the lifetime of the crop. Therefore, the initial functional unit will be the total production of each crop on a per hectare basis. These results are then changed to a per kg basis for use in the net energy analysis (see Chapter 9) and the full life cycle (see Chapter 10).

Systems boundaries include all field operations, diesel and fertiliser inputs, machinery use, etc. Figure 6-1 and Figure 6-4 summarise the system boundaries for each crop. Each life cycle begins at the propogule, or cuttings required for each crop and ends after the crop is harvested. This makes the LCA a ‘cradle to farm-gate’ study. The goal and scope for the LCA study is the same for both Miscanthus and SRC Willow.

6.2 LIFE CYCLE INVENTORY

The life cycle inventory (LCI) stage of an LCA is where the majority of the data collection occurs. In this section the LCI for the production of one hectare of Miscanthus is set out first, followed by the LCI for SRC Willow. For both crops it has been assumed that agricultural land has been used, therefore no land use change is included in the LCI, but land occupation is incorporated. This is modelled in SimaPro as ‘land transformation’ and ‘land occupation’. For both crops transformation is one hectare ‘from arable’ and ‘to arable’, and occupation is one hectare per year of production.

6.2.1 Production of one hectare of Miscanthus

In order to develop a life cycle model, some assumptions are required to form a base case for Miscanthus production. It is acknowledged that the exact inputs will vary by location due to differences such as soil type, soil quality, local weather conditions, gradient of land, farming practice, and so on. Therefore the base case assumptions are assessed in the sensitivity analysis to validate their significance, and to account for varying local conditions. The data outlined below have been used to compile the LCI for the production of Miscanthus. It has been assumed that the Miscanthus plantation will remain viable for 18 years (16 full harvests after establishment). The main operations, material and energy inputs in the production of one hectare of Miscanthus (see Figure 6-1) are presented in the following sub-sections.

6.2.1.1. Propagule Supply

Propagule supply is the plant material used for the purpose of plant propagation. For Miscanthus this comes in the form of rhizomes which are planted out to produce the crop. It was considered important to take account of the inputs required to produce the propagule starting material; this does not often appear to have been accounted for in other LCA studies e.g. (Smeets *et al.*, 2009). Nonetheless, the rhizome material is a vital part of Miscanthus cultivation. The main method of propagation currently used in the UK is rhizome division, which is favoured because it is less expensive and generally produces vigorous plants (DEFRA, 2007b). The production of rhizomes for the propagation of the Miscanthus was treated as a separate crop. Production inputs, taken from (Bullard & Metcalfe, 2001), had the following assumptions:

- a one hectare field is established 3 years previously and harvested to obtain the rhizome material;
- all inputs of crop management over the 3 years are included;
- rhizomes are lifted using a plough to loosen the soil and a rotary cultivator;
- rhizomes are then harvested using a bulb harvester;
- rhizomes are transported to storage and kept until required in the field.

The main inputs for popagule supply are the diesel and lubricating oil used in harvesting operations, fertiliser and herbicide inputs, and transportation to storage. Successful removal of rhizomes yields 10t/ha of rhizomes averaging 50g in weight (Huisman & Kortleve, 1994). One tonne of this graded material is sufficient to re-plant at a density of 20,000 per hectare, therefore only 1/10th of a hectare of rhizomes is required to plant one hectare. Lewandowski *et al.*, (1995) describes an alternative propagation method commonly used in Germany, this is analysed in the sensitivity analysis (see section 6.4.1).

6.2.1.2. Site Preparation

Agricultural land needs to be prepared prior to planting. Thorough site preparation is essential for good establishment, ease of subsequent crop management and high yields (DEFRA, 2007b). Prior to cultivation 3 tonnes of lime is applied to reduce soil acidity, this operation is undertaken to decrease long-term acidity problems (Agricultural Lime Association, 2008; Bullard & Metcalfe, 2001). The land is assumed to be heavy clay, is sub-soiled then ploughed and disked once using a 113 HP tractor, each operation takes one pass. A clay soil is selected because over 50% of the arable cropping area in the UK is within this land soil structure classification (NSRI, 2008). This choice of cultivation is consistent with current DEFRA guidance, and previous studies (Bullard & Metcalfe, 2001; DEFRA, 2007b).

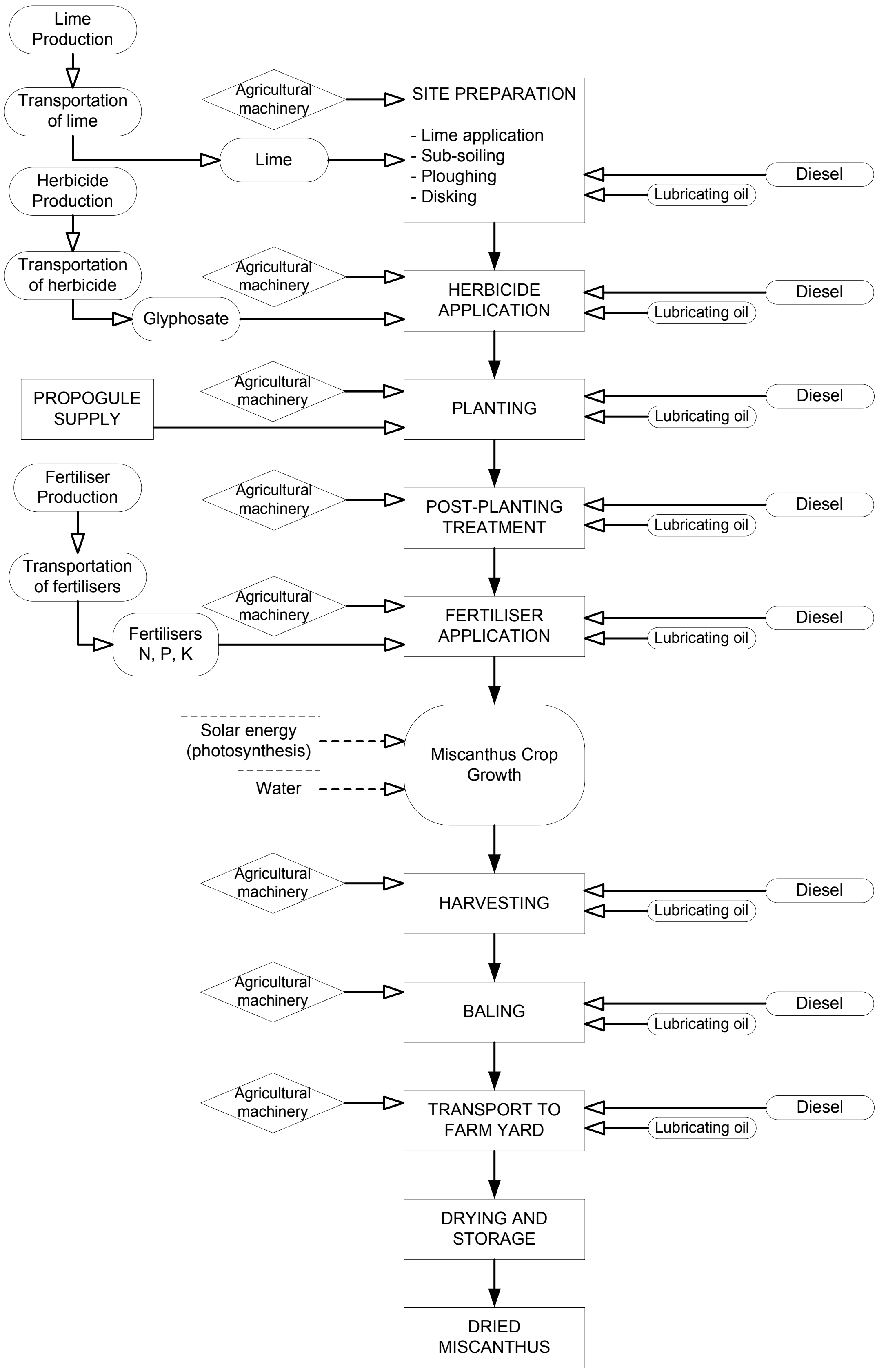


Figure 6-1: System boundary for the production of Miscanthus

6.2.1.3. Herbicide

An initial broad spectrum herbicide (i.e. glyphosate) application is required to control perennial weeds (DEFRA, 2007b). This operation requires one pass using an 80 HP tractor and sprayer with a 24m sprayboom. Weed control products and requirements will vary depending on site, weed burden and species composition. Conversations held with two farmers growing Miscanthus in the South West indicated that no subsequent weed control is required due to the canopy protection Miscanthus growth provides (T. Barton, Wadswick Farm, Corsham, Wiltshire, 2010, personal communication; G. Mead, Holt Farms, Blagdon, Somerset, 2010, personal communication).

6.2.1.4. Planting

Planting is assumed to be undertaken with a semi-automated potato planter (Bullard & Metcalfe, 2001). This method was until recently the most common for planting rhizomes, and has demonstrated success on a range of soils in the UK and Europe (Venturi *et al*., 1999). Alternative planting methods for Miscanthus have emerged in recent years. The use of a specialist Miscanthus planter is evaluated in the sensitivity analysis.

6.2.1.5. Post planting treatment

Following planting the field is rolled with a soil consolidation device to prevent the rhizomes from drying out (DEFRA, 2007b).

6.2.1.6. Fertiliser applications

Annual fertiliser demands of the crop are very low, due to good nutrient use efficiency and the plant's ability to recycle large amounts of nutrients into the rhizomes during the latter part of the growing season (DEFRA, 2007b). In year 1, 100 kg Nitrogen (N), 60 kg Potassium (K) and 40 kg Phosphate (P) per hectare, are applied with a broadcaster fertiliser spreader (Bullard & Metcalfe, 2001). Under UK growing conditions, fertilisers are not usually applied after establishment (T. Barton, Wadswick Farm, Corsham, Wiltshire, 2010, personal communication). Therefore, for the base case, it is assumed that no subsequent fertiliser applications are applied. Mineral (inorganic) fertilisers were assumed to be used as these are the most commonly used in UK arable farming. Data for the production of the fertilisers was taken from the Ecoinvent database (Swiss Centre for Life Cycle Inventories, 2009).

6.2.1.7. Harvesting

It is assumed that a self-propelled forage harvester followed by a baler that delivers large bales is used. The standing crop first cut with a forage harvester into a swath (DEFRA, 2007b) and then baled. This was the standard practice with the Miscanthus producing farms visited for the case studies (see Figure 6-2). Yields from the harvest are taken as 0t, 12t & 24t ha^{-1} of fresh biomass at 50% moisture (0, 6 & 12 odt) in years 1, 2 and 3-18 respectively (DEFRA, 2007b; DEFRA, 2007d). Alternative yields are analysed in the results section (see section 6.3.3.1).

6.2.1.8. Baling

Baling is performed using a Hesston baler, moisture content having declined to 25% (Bullard & Metcalfe, 2001). A bale mass of 600kg per bale is assumed (Huisman & Kortleve, 1994). Bales are loaded onto a trailer and carted to the farm over an average distance of 1km.

Figure 6-2: Self-propelled forage harvester at Wadswick Farm, April 2010

6.2.1.9. Post cultivation

It is assumed that the land is ploughed and disked once the Miscanthus plantation reaches the end of its lifetime. This is to return the land to its pre-plantation state. Ploughing and disking operations are the same as site preparation (see section 6.2.1.2).

6.2.1.10. Drying and Storage

Drying involves the extraction of moisture from the product by natural ventilation and radiation or by artificial ventilation with ambient or heated air. The moisture content should decrease to a level which is in equilibrium with a relative air humidity of 70-80% depending on the storage temperature (Jones & Walsh, 2001). Too high a moisture content can lead to dry matter losses which reduces the calorific value; and fungal spore contamination which can be damaging to human health.

Different methods can be applied to dry Miscanthus to a moisture content which allows storage of the harvested biomass in a suitable way. Drying in the field is the method which is assumed for the base case, as using the ambient air and solar radiation is the most cost effective method. It is also the simplest way to dry the biomass and most likely to be used by farmers. Drying in the field does not have any inputs or outputs for the LCI. Alternative methods of drying are assessed in further detail in the sensitivity analysis (see section 6.4.1)

Miscanthus bales are assumed to be stored under cover, as uncovered bales gain moisture content with resultant degradation of material quality (Nolan *et al*., 2008). A storage volume of 4m^3 per tonne is assumed, based upon the bale dimensions of 0.9x1.2x2m and typical bale weights of 600 kg at 25% moisture content. Storage facilities are necessary as the fuel will be needed all year. The construction of a permanent barn has been included in the study. Such a barn was assumed to consist of a concrete floor, steel framework with steel cladding, and concrete blocks (Elsayed & Mortimer, 2001). This type of barn was visited at Holt Farms in Blagdon, Somerset, where the inventory was confirmed (see Figure 6-3). Using existing storage facilities are assessed in the sensitivity analysis.

Figure 6-3: Storage barn at Holt Farms, March 2010

6.2.2 Production of one hectare of SRC Willow

This section follows a similar format to the previous section on Miscanthus production. Data outlined below have been used to compile the life cycle inventory for the production of one hectare of SRC Willow. Again it is acknowledged that there will be localised variations in the inputs required, so a sensitivity analysis is undertaken (see section 6.4.1). The system boundary is outlined in Figure 6-4. It has been assumed that the SRC Willow plantation will remain viable for 23 years (7 full harvests on a 3-year cycle after establishment) (DEFRA, 2002). The main operations, material and energy inputs in the production of one hectare of SRC Willow are presented in the following sub-sections.

6.2.2.1. Cuttings supply

Plant cuttings are taken from a parent plant, to create a new plant which is independent of the parent. It is also known as 'cloning' as cuttings will grow to be very similar to the parent plant. A review of other LCA studies undertaken on Willow production revealed that consideration is not always given to cuttings supply. This is surprising as cuttings are an indispensable part of the production process. They require various inputs of energy and materials to be available for commercial planting. Therefore, the inclusion of cuttings supply in the life cycle inventory was considered important for this study.

The production of Willow cuttings for cultivation was treated as a separate crop. Production inputs, adapted from (Matthews, 2001), had the following assumptions:

- a one hectare field is established one year previously and harvested to obtain the willow cuttings;
- all inputs of crop management over the year are included;

- cuttings are lifted using a plough to loosen the soil and then harvested using a brushcutter;
- cuttings are transported to storage and kept until required in the field.

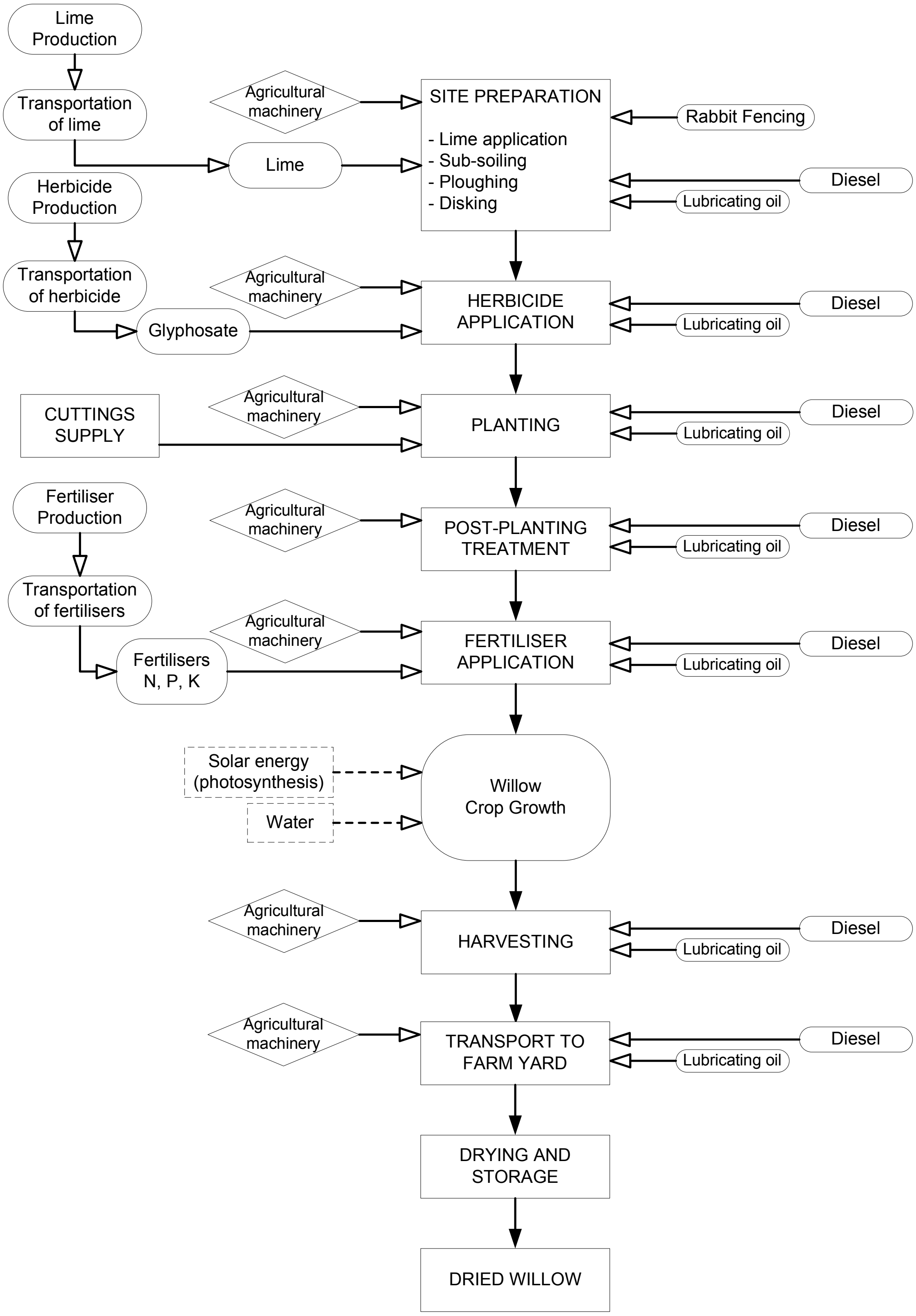


Figure 6-4: System boundary for the production of SRC Willow

6.2.2.2. Site Preparation

The agricultural land used to produce SRC Willow requires the same preparation as Miscanthus (DEFRA, 2002) (see section 6.2.1.2). In addition it is recommended that rabbit fencing is erected to protect the crop during its vulnerable stage up to first harvest (DEFRA, 2002). The fencing requires support posts, fencing wire, preservative and staples. The recommended design of wire-mesh netting fence should be a minimum of 75cm high with a further 15 cm lapped on the surface (DEFRA, 2004). The wire fencing is supported by wooden stakes 1.7m high, and 7cm in diameter, placed up to 15m apart, with end posts 2.1m high and 11cm in diameter (DEFRA, 2004). For this study it has been assumed that one hectare is 100m x 100m, which gives a circumference of 400m. This means that the total materials required for the fencing are as follows:

- 390 m^2 (90cm x 400m) of wire mesh fencing;
- 4 end posts, one for each corner;
- 23 wooden stakes, one every 15m minus the four end posts;
- 20kg wood preservative in total, to cover all 27 end posts and wooden stakes;
- 1 kg of staples, to attach wire mesh fencing to stakes.

6.2.2.3. Herbicide

Weed control is a vital part of coppice establishment. Complete eradication of all invasive perennial weeds is crucial prior to planting. It assumed that one application of a glyphosate-based herbicide is applied prior to planting (DEFRA, 2002). This operation requires one pass and uses the same method as Miscanthus (see section 6.2.1.3). Additional applications of glyphosate are assumed to be applied after each harvest (DEFRA, 2002), giving 8 applications altogether in a 23 year cycle. This application method was consistent with that employed by a Willow farmer from the South West (A. Hughes, Long Ashton Research Farm, Bristol, 2010, personal communication). The requirement for pesticides and herbicides is site specific, therefore this study only considers the application of glyphosate. The effect of no and high herbicide applications are considered further in the sensitivity analysis (see section 6.4.1)

6.2.2.4. Planting

Willow rods were assumed to be planted using a step planter (also known as a transplanter). This machine cuts the rods into 18-20cm cuttings, inserts the cuttings vertically into the soil and firms the soil around each cutting (DEFRA, 2002). 15,000 cuttings per hectare is the current standard commercial planting density using this method (DEFRA, 2002). One pass is required using an 80 HP tractor.

6.2.2.5. Fertiliser Applications

SRC Willow has a low demand for Nitrogen (N) and the current UK recommendations for application are 40, 60 and 100kg N/ha/yr for the 1st (i.e. after cutback), 2nd and 3rd years of the harvest cycle respectively (Johnson, 1999). However, no fertiliser should be applied during the establishment year, i.e. from planting until after the post-cutback (DEFRA, 2002). This is because during the first growing season, the nutrient capital is generally adequate for establishment, and the crop will not have developed the necessary root system for effective uptake. Fertiliser application can be difficult from the 2nd year (after cutback) onwards (DEFRA, 2002).

An application of 200kg N/ha was assumed to be applied in the first year (after cutback) of every three years. This gives a total of 7 applications during a 23 year cycle. For Phosphate (P) 42kg P/ha is assumed to be applied in year 2 and every 3 years thereafter (Styles & Jones, 2007). Potassium (K) is applied at the same time as the other fertilisers, with amounts of 100kg K/ha in year 2 and every 3 years after that (Johnson, 1999).

Various literature sources suggest different amounts of fertiliser application. This can cause some difficulties when choosing what application rates to include in the LCI. A further problem is the type of fertiliser chosen, for example organic fertilisers such as sewage sludge can be used on energy crops, or more traditional mineral (inorganic) fertilisers. As with Miscanthus, it was decided to choose the most common application rates from the literature for UK conditions. The amounts applied are consistent with the South West Willow farmer (A. Hughes, Long Ashton Research Farm, Bristol, 2010, personal communication). The data used for mineral fertilisers was selected as described for Miscanthus (see section 6.2.1.6). Different fertiliser application rates and fertiliser types are assessed in the sensitivity analysis

6.2.2.6. Harvesting

Harvesting generally takes place on a 3-year cycle, the first harvest being 3 years after cutback (DEFRA, 2002). Direct-chip harvesting is taken as the base case, where the stems are cut and then blown into an accompanying trailer. This operation requires one pass using a direct chip harvester. The chips are then transported to storage using the trailer. Yields are assumed to be 24 odt per harvest, (or 8 odt/ha/yr) (DEFRA, 2007d). The trailer has a load capacity of 10 tonnes so three trailer loads are required to transport the wood chip back to storage. An average distance of 1km each way is assumed for this transportation (i.e. 6km in total).

6.2.2.7. Storage & Drying

Direct-chip harvesting is currently more efficient than rod harvesting; however storage and drying of the fresh wood chip can cause problems. Stored, fresh wood chip can heat up to 60°C within 24 hours and start to decompose (DEFRA, 2002). During decomposition calorific value of the fuel is lost, and the fungal and bacterial spores produced during decomposition constitute a health hazard (AEA, 2009b). It is currently considered uneconomical to dry wood chip by any method other than natural air drying; which is therefore used for the base case this study. Alternative drying methods, such as the use of grain driers, ventilated-floor-driers and low-rate aeration using ducts are considered in the sensitivity analysis (see section 6.4.1). Storage facilities included in the study are assumed to be the same as used in Miscanthus production (see section 6.2.1.10).

6.2.3 Other data required for the LCI

Sections 6.2.1 and 6.2.2 outline the field operations required for Miscanthus and SRC Willow respectively. In addition to these, several other inputs and outputs are required to complete the LCI for each crop. These include diesel production and use, lubricating oil consumption, agricultural machinery, direct field emissions, and carbon sequestration. The following sub-sections outline the LCI data which have been included within the system boundary for each crop.

6.2.3.1. Diesel consumption

The assumed diesel use for each operation outlined in sections 6.2.1 and 6.2.2 is based on the work rate (h/ha), number of passes, and fuel use per hour. Up to date work rates for farm operations were taken from (Nix, 2008), with the exception of bale moving and loading which was taken from Bullard & Metcalfe (2001). The number of passes depends on how many times the operation occurs during the life time of the cultivation. For example, several operations only require one pass during establishment, whereas harvesting Miscanthus requires 16 passes, once in each year. Nix (2008) assumes the use of four-wheel drive 75-90 kW (100-120 HP) tractors for ploughing, heavy cultivation and other work with a high power requirement. Four-wheel drive 55-65 kW (75-87 HP) tractors are assumed for all other operations (Nix, 2008). Published work rates are based on tractors in these power ranges. To use these work rates two tractors in the middle of the power ranges were selected (see Table 6-1). The OECD undertakes tests of most commercial tractors (OECD, 2009). From the OECD database, fuel consumption was found to be very similar in a range of tractor makes at a given power. Therefore, the make of tractor was not considered important when determining fuel use. The tractors selected were both manufactured by John Deere, as this is the most common make used in the UK (Agricultural Engineering Association, 2009).

Table 6-1: Tractor diesel consumption (source: OECD, 2009)

Power	Make	Model	Fuel consumption (litres / hour)	OECD Approval number
59.9 kW (80 HP)	John Deere	6215	19.15	2/2 237
84.2 kW (113 HP)	John Deere	6420 S	23.64	2/2 032

Table 6-2 outlines the tractor requirement, machinery used, workrate to calculate diesel fuel use and lubricating oil for each field operation. Emissions from machinery use (i.e. diesel fuel and lubricating oil) are taken from the Ecoinvent database.

6.2.3.2. Lubricating oil

Lubricating oil consumed in the tractors is included within the LCI. Lubricating oil consumption data (see Table 6-2) was derived from machinery management data in literature (ASABE, 2008; Heller *et al.*, 2003). As stated above, emissions for the use of lubricating oil are from Ecoinvent.

6.2.3.3. Farm Machinery

For each farm operation the machinery used was identified. In most cases, this involves a tractor and one other item of farm machinery, e.g. tractor and trailer. The estimated useful economic life-time (UEL) of machinery was then found based on the number of work units (WU) worked (hectares or hours) in one year. Finally, the weight of each item of farm machinery was found from an equipment supplier. From this data, the weight of the tractor and machinery can be allocated to each operation. An allocation factor based on kg per WU is used, as the functional unit of machinery is one kilogram machine during its entire lifetime.

Allocation Factor [kg/WU] = Weight [kg] / Lifetime [WU] (eq. 6.1)

Table 6-3 displays the above information for each item of agricultural machinery, which accounts for farm machinery production. The use of farm machinery is accounted for above via diesel and lubricating oil consumption.

Table 6-2: Diesel and lubricating oil consumption for different field operations

Field operation	Tractor Requirement (HP)	Machinery used	Workrate (h/ha)	Diesel use per pass (litres)	(MJ)	Lubricating oil (litres)
Lime application	80	Broadcaster	1.6	30.64	1,115	0.01
Sub-soiling	113	Subsoiler	1.33	31.52	1,147	0.04
Ploughing	113	Plough	1.33	31.52	1,147	0.11
Disking	113	Disc harrow	0.67	15.76	574	0.03
Weed control	80	Sprayer	0.27	5.11	186	0.01
Planting (Miscanthus)	80	Planter	3.2	61.28	2,231	0.13
Rolling (Miscanthus)	113	Roller	1.33	31.52	1,147	0.03
Planting (Willow)	80	Transplanter	3.2	61.28	2,231	0.13
Fertiliser application	80	Broadcaster	0.27	5.11	186	0.01
Harvesting	n/a	Self propelled forage	1.6	28.42	1,034	0.08
Baling	80	Baler	0.9	21.28	558	0.06
Moving bales	80	Trailer	0.36	6.89	251	0.01
Bale loading	80	Bale loader	0.36	6.89	251	0.01
Harvesting (Willow)	80	Direct chip harvester	1.65	31.55	1,148	0.08
Moving Willow	80	Trailer	0.36	6.89	251	0.01
Source	Nix, 2008		Nix, 2008; Bullard & Metcalfe, 2001	Calculated	Calculated	ASABE, 2008; Heller et al. 2003

Table 6-3: Agricultural Machinery – weights, lifetime, working units & allocation

Machinery	Weight (kg)	Life-time (years)	Working Unit (WU)	Utilisation (WU/year)	Life-time (WU)	Allocation (kg/WU)
Tractors & Trailer						
Tractor, 80 HP	4,240	12	h	750	9000	0.47
Tractor, 113 HP	5,280	12	h	750	9000	0.59
Trailer	2,600	12	h	250	3000	0.87
Agricultural machinery, tillage						
Subsoiler	805	12	ha	50	600	1.34
Plough	1,050	12	ha	40	480	2.19
Disc harrow	1,400	12	ha	50	600	2.33
Roller	750	12	ha	25	300	2.5
Agricultural machinery, harvesting						
Forage Harvester	11,440	12	ha	100	1,200	9.53
Direct chip harvester	13,180	12	ha	100	1,200	10.98
Agricultural machinery, general						
Broadcaster	200	10	ha	100	1000	0.2
Sprayer	200	10	ha	100	1000	0.2
Potato Planter	1,150	12	ha	50	600	1.92
Transplanter	1,134	12	ha	50	600	1.89
Baler	6,840	15	ha	65	975	7.02
Bale loader	621	15	ha	65	975	0.64
Bushcutter	2,220	12	ha	50	600	3.7
Source	Various (see Appendix)	Various (see Appendix)		calculated	calculated	calculated

Machinery is allocated between the considered farm operation and other usages using the information on weight, operation time and lifetime (see Appendix E). If the WU is in hours (only tractors and trailer) then the allocation factor (kg/WU) is multiplied by the workrate (h/ha) to give the allocation on a per hectare basis. If the WU is in hectares then the allocation factor is already on a per hectare basis (N.B. It is only tractors and trailers which have hours for their WU, all other machinery is on a per hectare basis).

To give an example, ploughing one hectare requires a 113 HP tractor and a plough. The tractor weighs 5,280 kg and can work a total of 9,000 hours, which gives an allocation factor of 0.59 (i.e. 5,280 / 9,000). It takes one hour and twenty minutes to plough one hectare, so the total tractor amount for ploughing is 0.75 kg (i.e. 0.59 * 1.333). The plough weighs 1,050 kg and can work a total of 480 hectares, which gives an allocation factor of 2.19 (i.e. 1,050 / 480). As the plough is only used for one hectare, then the total plough amount is 2.19 kg (as the WU is already in hectares). Table 6-4 summaries the amount of tractor and agricultural machinery allocated to each field operation, which is calculated based on the workrate and allocation (shown in Table 6-3).

Table 6-4: Tractor and agricultural machinery allocated to each field operation

Activity name	Tractor (HP)	Machinery	Workrate (h/ha)	Tractor (kg)	Machinery (kg)
Site Preparation					
Lime application	80	Broadcaster	1.6	0.75	0.2
Sub-soiling	113	Subsoiler	1.33	0.78	1.34
Ploughing	113	Plough	1.33	0.78	2.19
Disking	113	Disc harrow	0.67	0.39	2.33
Herbicide					
Weed control	80	Sprayer	0.27	0.13	0.2
Planting					
Planting (Miscanthus)	80	Planter	3.2	1.51	1.92
Rolling	113	Roller	1.33	0.78	2.5
Planting (Willow)	80	Transplanter	3.2	1.51	1.89
Fertiliser					
Fertiliser application	80	Broadcaster	0.27	0.13	0.2
Harvesting					
Harvesting (Miscanthus)	n/a	Forage Harvester	1.6	n/a	9.53
Baling	80	Baler	0.8	0.38	7.02
Moving bales	80	Trailer	0.36	0.17	0.31
Bale loading	80	Bale loader	0.36	0.17	0.64
Harvesting (Willow)	n/a	Direct chip harvester	1.65	n/a	10.98

Having allocated the farm machinery for each operation the inventory was generated. Data from existing literature was used as there are many comprehensive studies published in the literature and in LCA databases. The Ecoinvent database categorises agricultural machinery into different classes, these include: tractors; tillage machinery; harvesting equipment; trailers; and general farm machinery (Swiss Centre for Life Cycle Inventories, 2009). Ecoinvent uses manufacturer's information and expert statements to estimate the typical composition (Nemecek & Erzinger, 2005). For each class used in this study, the typical composition of materials used is shown in Table 6-5.

Table 6-5: Typical composition of different agricultural machinery classes (source: (Nemecek & Erzinger, 2005)

Material	Machinery classes				
	Tractor	Trailer	Machinery, tillage	Harvesters	Machinery, general
Steel, unalloyed	67%	70%	84%	70%	84%
Steel, alloyed	10%	5%	15%	10%	11%
Other metals	8%	19%	1%	8%	1%
Rubber	10%	5%	0%	7%	3%
Plastics	3%	0%	0%	3%	0%
Others (glass, paints, etc.)	2%	1%	0%	2%	1%

Manufacturing, maintenance, repair and disposal of the machinery are included, as well as transportation from manufacture in mainland Western Europe to the farms in the UK. Table 6-5 shows that steel is the most important material. The synthetic-rubber content is determined primarily by the tyres. Material composition not only varies between different classes of machine, it also varies slightly between different models. However, this data reflects an average and typical composition for each class of machinery, and is sufficient for the purposes of this LCA study. Where a published inventory could not be found, general farm machinery was used on a per kg basis.

6.2.3.4. Direct Field Emissions

Using mineral fertilisers in the production of crops causes emissions to the soil, water and air. These direct field emissions have been accounted for in the LCA study due to the use of different fertilisers. The following emissions have been included within the study:

- Emissions of Ammonia (NH_4) to Air
- Nitrate Leaching (NO_3) to Ground Water
- Emissions of Phosphorus (P) to Water
- Emissions of Nitrous Oxide (N_2O) to Air
- Emissions of NOx to Air

Details of the modelling of these direct field emissions have been included in Appendix E.

6.2.3.5. CO_2 fixation in biomass

Carbon dioxide (CO_2) is a naturally occurring compound or an anthropogenic emission, and takes part in the so-called geochemical carbon cycle (Guinee *et al.*, 2009). CO_2 is sequestered in biomass during growth from the atmosphere. Rabl *et al.* (2007) discuss how to account for the removal of CO_2, in biomass, from the atmosphere. The most appropriate way to treat biogenic carbon cycles is to view them as genuine cycles (Rabl *et al.*, 2007). There is growing consensus in the LCA community that the removal of CO_2 should be counted explicitly for in biomass production (Guinee *et al.*, 2009). Consequently, at the systems level, it is necessary to calculate the fixation of CO_2 during crop growth. In a bioenergy system, this CO_2 will later be emitted during energy conversion.

To calculate the amount of CO_2 in biomass, it is first necessary to find the carbon content of the biomass. This can be found using the Phyliss database (ECN, 2009). Carbon (C) has an atomic weight of 12 (2 s.f.), and oxygen is 16 (2 s.f.). The atomic weight of CO_2 is therefore 44 (2 s.f.). This gives a ratio of CO_2 to C of approximately 3.66 (i.e. 44/12). Using the carbon content of the biomass, the total CO_2 fixed per kg of biomass will be:

Total CO_2 fixed (kg) = Tb * Cc * 3.66 (Eq. 6.2)

Where Tb = Total biomass (kg), Cc = Carbon content of biomass (% weight)

6.2.3.6. Soil carbon

Carbon sequestration in soil has not been included in this LCA study. However, it is acknowledged that there are a number of factors which can influence the amount of soil organic carbon (SOC). A discussion has therefore been included in Chapter 10.

6.3 LIFE CYCLE IMPACT ASSESSMENT

Having obtained sufficient data for the LCI, the next stage of the LCA was to complete the life cycle impact assessment (LCIA). This section first presents the impact assessment results on a per hectare basis for Miscanthus and then SRC Willow. The impacts attributed to the material and energy inputs per hectare are independent of the subsequent yield of the crop, i.e. the impacts associated with crop production per hectare will occur regardless of the crop yield, whereas crop production impacts per kg of biomass produced are dependent on the crop yield. Therefore the starting point for this section is to present LCIA results on a per hectare basis, over the lifetime of each crop. Results are then presented on a per kg basis for a range of different yields. As the impact assessment results are based on the data and assumptions of the LCI (see section 6.2) a sensitivity analysis was undertaken to identify which parameters had the largest effects on the results of the study. Results are presented using the impact assessment approach outlined in Chapter 3.

6.3.1 Production of one hectare of Miscanthus

6.3.1.1. ReCiPe (endpoint)

Characterised results for the production of one hectare of Miscanthus over its assumed lifetime of 18 years are displayed in Figure 6-5. Harvesting and baling were found to be the stages of the life cycle which contributed the most to each impact category, with the exception of freshwater eutrophication and agricultural land occupation.

Normalised results for ReCiPe (endpoint) indicated that fossil fuel depletion was the most important impact category, followed by agricultural land occupation, climate change and particulate matter formation (see Figure 6-6).

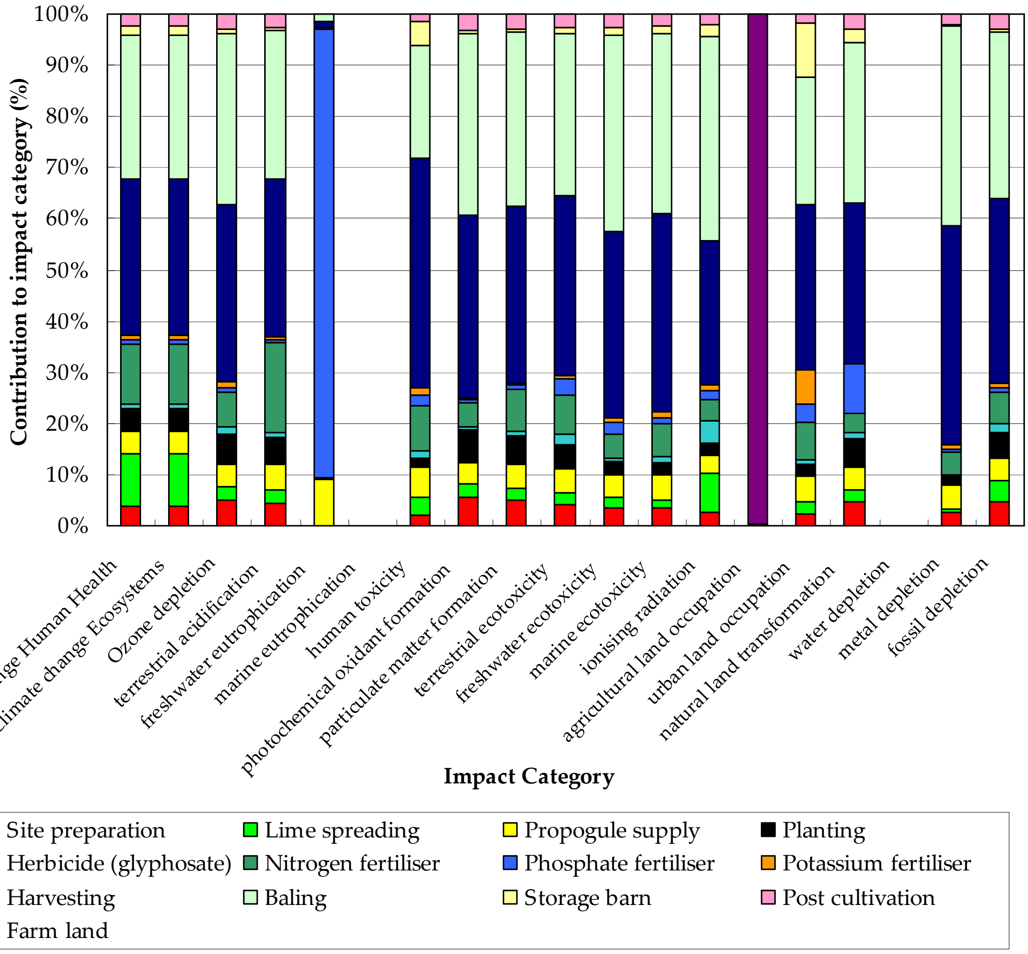


Figure 6-5: Characterised Data for the production of one hectare of Miscanthus – ReCiPe endpoint (H)

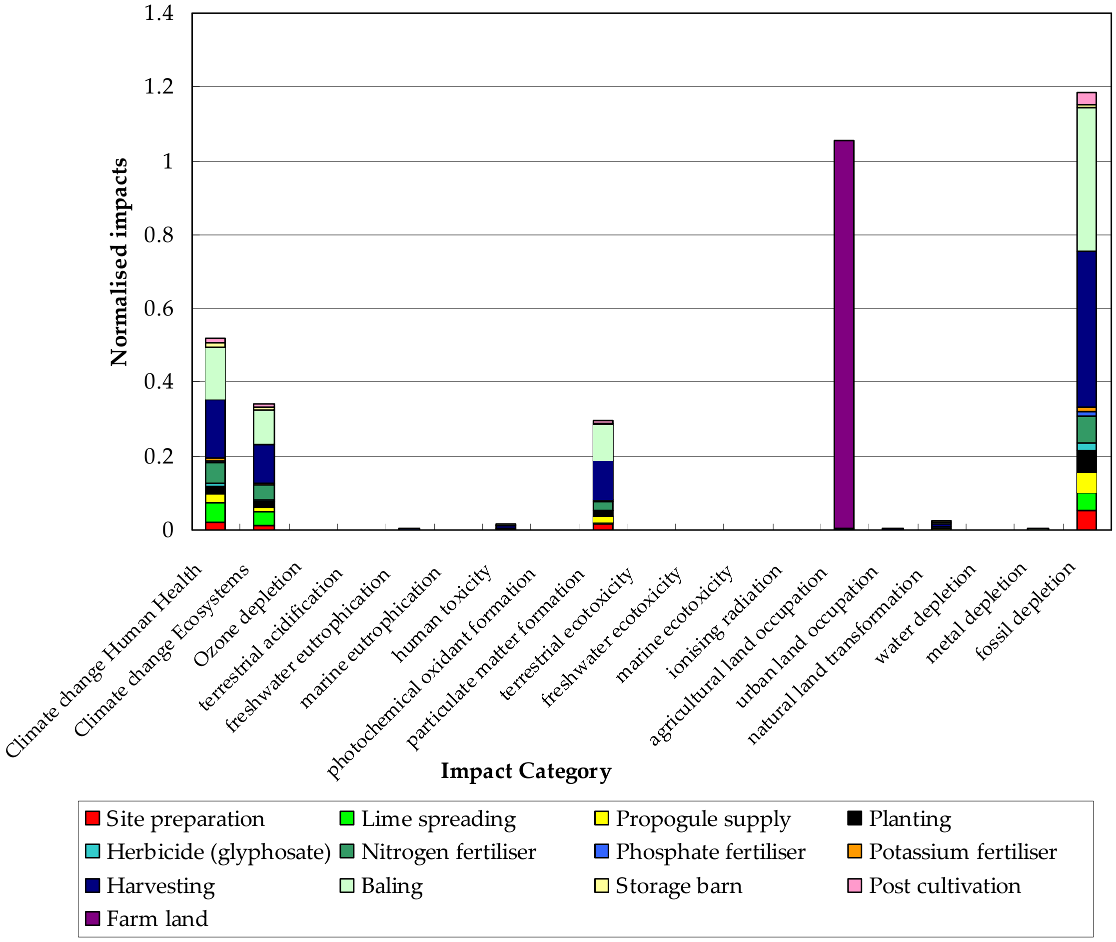


Figure 6-6: Normalised Data for the production of one hectare of Miscanthus – ReCiPe endpoint (H/A)

6.3.1.2. Eco-Indicator 99

Results for the production of one hectare of Miscanthus using Eco-Indicator 99 show very similar findings as ReCiPe (endpoint). Harvesting and baling make the biggest overall contributions to most impact categories. Normalised results display the results in a slightly different order (see Figure 6-6) but confirm the four most important impact categories as land use, fossil fuel depletion, climate change and respiratory inorganics. It should be noted that the CO_2 fixation in Miscanthus growth has not been included in Figure 6-6. If it was climate change would display a negative impact becomes the most significant impact category due to the carbon sequestration benefit at farm-gate (see Chapter 10).

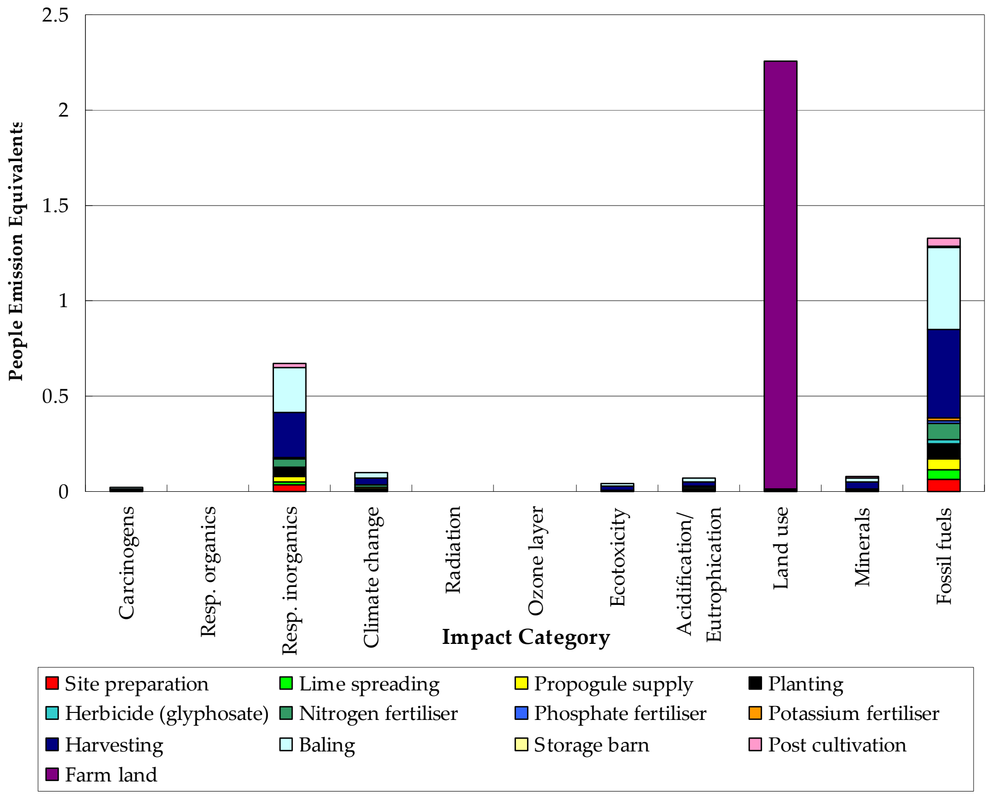


Figure 6-7: Normalised Data for the production of one hectare of Miscanthus – Eco-Indicator 99 (H)

6.3.1.3. ReCiPe (midpoint)

Both endpoint methodologies used in the study demonstrate very similar findings and highlight the key issues. Hence fossil fuel depletion, agricultural land occupation, climate change and particulate matter formation were assessed in more detail using ReCiPe (midpoint).

- Harvesting contributed most to fossil fuel depletion (36%), followed by baling (33%) and the use of nitrogen fertiliser (6%), with all other life cycle stages contributing 5% or less.
- Analysis of harvesting and baling showed that it was primarily the use of diesel fuel which contributed to fossil fuel depletion, although the allocation of farm machinery also made up about 10% of the contribution. This is understood as this is an annual field operation whereas most other operations are only performed once.
- Particulate matter formation was directly related to the combustion of fossil fuels in these life cycle stages.
- Climate change is also closely related to fossil fuel consumption, with harvesting (31%) and baling (28%) making the biggest contributions followed by nitrogen fertiliser (12%) and lime spreading (10%).
- Land use is dominated by the use of farm land in the growth of the crop itself.

6.3.2 Production of one hectare of SRC Willow

6.3.2.1. ReCiPe (endpoint)

Characterised results for the production of one hectare of SRC Willow over its assumed lifetime of 23 years are portrayed in Figure 6-8. It can be seen that the use of fertilisers and herbicide make up the majority of each impact category, with the exception of agricultural land use. In particular nitrogen fertiliser is the dominant life cycle stage in most impact categories. Other notable life cycle stages include the supply of Willow cuttings and the harvesting of the Willow.

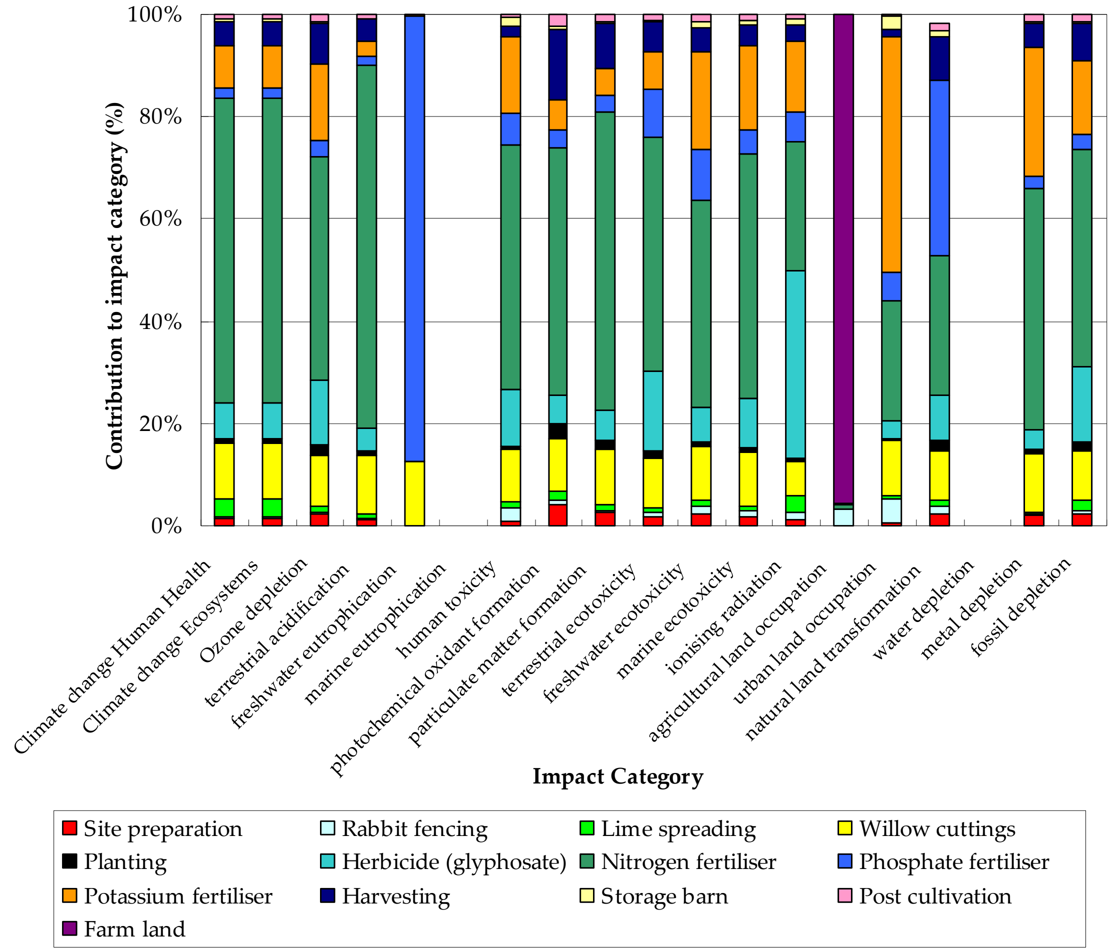


Figure 6-8: Characterised Data for the production of one hectare of SRC Willow – ReCiPe endpoint (H)

Normalised results for ReCiPe (endpoint) follow a similar pattern to that of the production of Miscanthus (see Figure 6-9), which gives a good indication of the potential impact categories of concern in the growth of perennial energy crops.

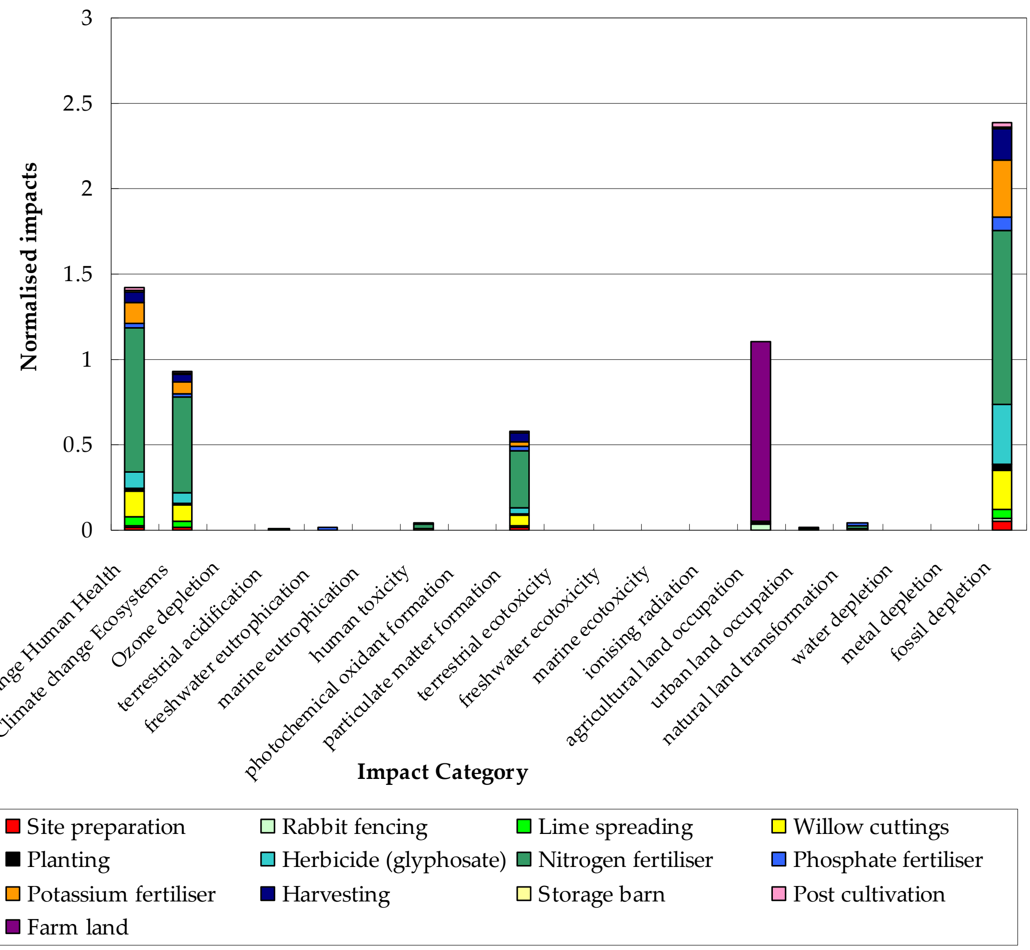


Figure 6-9: Normalised Data for the production of one hectare of SRC Willow – ReCiPe endpoint (H/A)

6.3.2.2. Eco-Indicator 99

Characterised results using Eco-Indicator 99 confirmed that the use of nitrogen fertiliser made the biggest contribution to each impact category. Other life cycle stages made analogous contributions to ReCiPe (endpoint). Normalised results (displayed in Figure 6-10) confirmed that fossil fuel depletion was the most important impact category, followed by land use, respiratory inorganics (particulate matter formation) and climate change. It can also be seen that acidification and eutrophication become more of a potential issue with SRC Willow, which is a reflection of the assumed higher application of agro-chemicals.

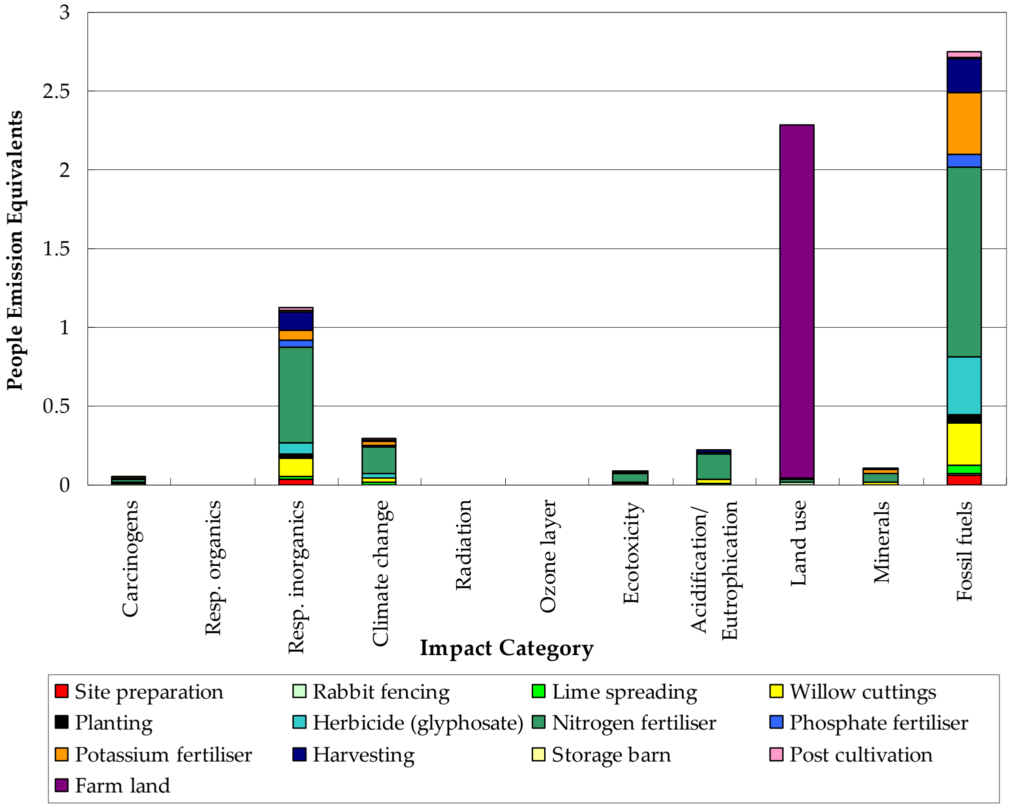


Figure 6-10: Normalised data for the production of one hectare of SRC Willow – Eco-Indicator 99 (H)

6.3.2.3. Recipe (midpoint)

Both endpoint methodologies applied for SRC Willow confirmed the impact categories of importance to further assess with ReCiPe (midpoint). Interestingly, these were consistent with the LCIA of Miscanthus which is a useful result.

- All life cycle stages were found to make some contribution towards fossil fuel depletion due to a combination of dependence on diesel for farming operations and upstream processes associated with materials and agro-chemical production.
- The most significant contribution towards fossil fuel depletion was the use of fertilisers and herbicide. In each of these the predominant use of fossil fuels was in the production of the agro-chemical. For example, in the production of nitrogen fertiliser large amounts of natural gas and heavy fuel oil are used to produce ammonia, the key material in ammonium nitrate.
- Nitrogen fertiliser contributes (42%) to fossil fuel depletion with herbicide (15%), potassium fertiliser (14%), Willow cuttings (10%) and harvesting (7%).
- Both climate change and particulate matter formation closely followed fossil fuel depletion, and therefore had a similar contribution breakdown.
- Land use is dominated by the use of farm land in the growth of the crop itself.

6.3.3 Production of one kilogram of biomass

Having presented the results for the production of one hectare of Miscanthus and SRC Willow, it is also valuable to display results for the production of one kilogram (1 kg). Only impact categories which were found to be significant in the normalised results or the sensitivity analysis are displayed in this section. Impacts associated with crop production on a per kilogram basis are directly related to the subsequent yield of the crop, i.e. the higher the yield the lower the associated environmental impacts will be. It was therefore considered necessary to display the results initially with one yield for each crop. The yields selected were based on a review of the literature, but consideration was also given to the general growing conditions in the South West of England. As the yields will vary depending on a number of variables, the results are subsequently presented to show the effect of a different range of yields (see Table 6-7 and Table 6-9).

6.3.3.1. Miscanthus

For Miscanthus an average yield of 12 odt/yr has been assumed. An assumption is made that the crop will remain viable for 18 years, with no harvest in year one, a 50% harvest in year two, and full harvests in years 3-18 (DEFRA, 2007b; DEFRA, 2007d). Therefore, over the crop lifetime 198,000 kg of Miscanthus will be produced per hectare. Table 6-6 displays the potential life cycle impacts of producing 1 kg of Miscanthus using ReCiPe LCIAM.

Table 6-6: Life cycle impacts for the production of 1 kg of Miscanthus – LCIAM: ReCiPe

Impact category	Midpoint Results		Endpoint Results	
	unit	Total	unit	Total
climate change human health	kg CO_2 eq.	0.05111	DALY	$7.155x10^{-08}$
climate change ecosystems	-	N/A	species.yr	$4.052x10^{-10}$
freshwater eutrophication	kg P eq.	0.00006	species.yr	$2.550x10^{-12}$
human toxicity	kg 1,4-DB eq.	0.00454	DALY	$3.178x10^{-09}$
particulate matter formation	kg PM_{10} eq.	0.00013	DALY	$3.294x10^{-08}$
agricultural land occupation	m^2a	0.05075	species.yr	$9.321x10^{-10}$
urban land occupation	m^2a	0.00049	species.yr	$9.379x10^{-12}$
natural land transformation	m^2	0.00002	species.yr	$3.095x10^{-11}$
water depletion	m^3	0.00045	$	0
metal depletion	kg Fe eq.	0.00643	$	0.00046
fossil depletion	kg oil eq.	0.01288	$	0.20698

LCIA results displayed in Table 6-6 are based on the LCI outlined in section 6.2.1 and a yield per annum of 12odt/ha/yr. The effect on life cycle impacts for a range of different yields is outlined in Table 6-7. This shows that lower yields will cause higher life cycle impacts per kg and vice versa.

Table 6-7: Effect on life cycle impacts for a range of different yields of Miscanthus

Yield per annum (odt/ha/yr)	Total yield over lifetime of crop (kg)	Effect on life cycle impacts (% change)
8	132,000	50.0%
9	148,500	33.3%
10	165,000	20.0%
11	181,500	9.1%
12	**198,000**	**0.0%**
13	214,500	-7.7%
14	231,000	-14.3%

6.3.3.2. SRC Willow

SRC Willow follows a different cropping pattern to that of Miscanthus. it also takes 2-3 years to fully establish (like Miscanthus) but it is then harvested every 3 years. An average yield of 24 odt per harvest has been assumed, which is equivalent to 8 odt/ha/yr (DEFRA, 2007d). It is assumed that the crop will remain viable for 23 years, with 7 full harvests in years 5,8,11,14,17,20 & 23 (n.b. it is cutback in year 2). Therefore, over the crop lifetime 168,000 kg of Willow will be produced per hectare.

Table 6-8: Life cycle impacts for the production of 1 kg of SRC Willow – LCIAM: ReCiPe

Impact category	Midpoint Results		Endpoint Results	
	unit	**Total**	**unit**	**Total**
climate change human health	kg CO_2 eq	0.13764	DALY	1.927×10^{-07}
climate change ecosystems	-	N/A	species.yr	1.091×10^{-09}
freshwater eutrophication	kg P eq	0.00048	species.yr	2.116×10^{-11}
human toxicity	kg 1,4-DB eq	0.00969	DALY	6.783×10^{-09}
particulate matter formation	kg PM_{10} eq	0.00028	DALY	7.285×10^{-08}
agricultural land occupation	m^2a	0.06406	species.yr	1.146×10^{-09}
urban land occupation	m^2a	0.00121	species.yr	2.340×10^{-11}
natural land transformation	m^2	0.00003	species.yr	5.822×10^{-11}
water depletion	m^3	0.00073	$	0
metal depletion	kg Fe eq	0.00951	$	0.00068
fossil depletion	kg oil eq	0.02880	$	0.46327

LCIA results displayed in Table 6-8 are based on the LCI outlined in section 6.2.2 and an equivalent yield per annum of 8 odt/ha/yr. The effect on life cycle impacts for a range of different yields is outlined in Table 6-9.

Table 6-9: Effect on life cycle impacts for a range of different yields of SRC Willow

Yield per harvest (odt/ha)	Yield per annum (odt/ha/yr)	Total yield over lifetime of crop (kg)	Effect on life cycle impacts (% change)
18	6	126,000	33.3%
21	7	147,000	14.3%
24	**8**	**168,000**	**0.0%**
27	9	189,000	-11.1%
30	10	210,000	-20.0%
33	11	231,000	-27.3%
36	12	252,000	-33.3%

6.4 LIFE CYCLE INTERPRETATION

Significant issues based on the LCI and LCIA have been discussed alongside the data and results in sections 6.2 and 6.3. Therefore this section presents the detailed sensitivity analysis which has been performed followed by a summary of the main findings and some recommendations for improvement.

6.4.1 Sensitivity Analysis

A sensitivity analysis was conducted to identify the parameters which had the largest effects on the results of the study. For both crops, various parameters were changed independently to analyse the effect on the LCIA results. The sensitivity cases assessed for each crop are summarised in Table 6-10, but the data used differed for each crop. Cases A to R for each crop were chosen based on the different possible iterations in the LCI. Each case therefore represents the possible variations in assumptions found during the course of the research. Full details (including the data and assumptions used) on each of these sensitivities is provided in Appendix F.

Table 6-10: Summary of sensitivity analysis cases for perennial energy crops

Case letter	Sensitivity case
A	Different propogule or cuttings method used
B	No lime is applied
C	Different planting method used
D	No herbicide applied
E	High herbicide application
F	No fertilisers applied
G	High nitrogen (N) applications
H	High phosphate (P) applications
I	High potassium (K) applications
J	High NPK Fertiliser applications
K	Organic fertiliser
L	Alternative harvesting method
M	Drying in storage
N	Drying in indstrial application
O	Storage facilities
P	Water use: Irrigation 1 (low)
Q	Water use: Irrigation 2 (medium)
R	Water use: Irrigation 3 (high)

Each sensitivity case was run using ReCiPe (midpoint) to quantify the effect on emissions and resource consumption relative to the base case for each crop. This produced a new set of LCIA results for each sensitivity case. ReCiPe (midpoint) was used as it provides stand-alone values and less uncertainty than endpoint LCIAMs. All impact categories were included in the sensitivity analysis. Due to the number of sensitivities which were run, the complete LCIA results for each case are included in Appendix F. Key findings from the sensitivity analysis include the following:

- An increased use of fertilisers had the biggest effect on the results in the sensitivity analysis. Applying high amounts of fertiliser (case J) caused the biggest increase to fossil fuel depletion, climate change and most other impact categories.
- With higher amounts of inorganic fertilisers, acidification and eutrophication were found to be potentially significant issues (cases G to J).
- Increasing the use of Nitrogen fertiliser (case G) was found to cause the biggest single increase in the impacts from Miscanthus growth.
- Increased herbicide application (case E) also made notable increases in all impact categories.
- In the base case for Miscanthus only initial fertiliser and herbicide applications are assumed. Whereas SRC Willow was assumed to have both fertiliser and herbicide applied after each cut back. The relative increases in impacts from higher agro-chemical applications were therefore greater for Miscanthus than for SRC Willow.
- Using high amounts of irrigation water (case R) caused notable increases in fossil depletion and climate change, and most importantly water depletion.
- Using organic fertiliser (case K) reduced all impact categories, but most notably freshwater eutrophication. However, in another study of the use of fertilisers in energy crop growth, it was found that using either type of fertiliser can lead to an increase in acidification and eutrophication (Gilbert *et al.,* 2011).
- Avoiding the construction of a storage barn (case O) made small reductions in impacts.
- Using artificial drying (cases M & N) increases several impact categories.

6.4.2 Improvement potential and recommendations

Findings from the LCIA and sensitivity analysis show that minimising fertiliser and herbicide inputs will greatly reduce the potential impacts perennial crop growth may have. Therefore it is recommended that wherever possible inorganic fertilisers are minimised or avoided, or alternatively organic fertilisers could be used. Gilbert *et al.* (2011) suggest any fertiliser should be avoided. The use of diesel in farming operations also makes notable contributions to the potential impacts from crop growth. Whilst this is somewhat unavoidable consideration could be given to using alternative fuel source such as biodiesel. Other ways to minimise diesel emissions can include using modern fuel efficient tractors and driving economically.

Artificial drying in industrial applications was found to greatly increase the potential impact of bioenergy crops. In particular, fossil fuel depletion and climate change were affected. It is therefore recommended that natural drying should be used where possible. Alternatively there is the possibility to use the heat from the biomass conversion processes. In both AD and gasification heat is generated during conversion from feedstock to biogas or producer gas and subsequent combustion of the fuel. Some of the heat could be used to dry perennial energy crops before they go through the conversion process.

6.5 SUMMARY

This chapter has completed a LCA case study for the production of both Miscanthus and SRC Willow. A LCI has been compiled for both crops based on UK growing conditions and tailored to the South West through consultation with farmers in the region. Subsequently a LCIA was performed which revealed that fossil depletion is the most important impact category for both crops. Closely related to the use of fossil fuels in the study are the impact categories climate change and particulate matter formation. Emissions such as CO_2 and NO_x arise from the combustion of fossil fuels in direct field operations and indirect processes such as fertiliser manufacture. Agricultural land occupation is also a potential issue due to the land requirements of growing crops. By utilising land for agriculture it prevents land from transforming back to its natural state and hence reduces the species diversity. Moreover agricultural land used for energy crops presents a potential issue of competition of land for the growth of food crops due the limited land available.

Overall the impacts of producing perennial energy crops were not found to be significant. When the endpoint damage categories are considered the numbers are very small indicating the potential damages are minimal. Nonetheless if perennial crops are grown on a large scale the total potential damages will become significant. For example, one of the primary drivers for an increase in bioenergy production is to provide a substitute for fossil fuels (see Chapter 4). If fossil fuel depletion becomes an issue with perennial energy crop growth, then it defeats the objective of bioenergy production in the first place. This is thus further assessed in the net energy analysis in Chapter 9, where it is shown that both Miscanthus and SRC Willow have very positive energy gain ratios. So although fossil fuel depletion is a potential issue, perennial energy crops can produce sufficient primary energy to displace some fossil fuel use.

Other potential issues which may arise from perennial crops growth are acidification and eutrophication. These impact categories were primarily affected by the use of agro-chemicals in cultivation. As perennial energy crops have a much lower demand for such inputs than annual food crops acidification and eutrophication are considered to be less of a potential issue. Nonetheless, it is recommended that the use of inorganic fertilisers and herbicides are minimised or avoided in order to maximise the potential benefit of perennial energy crops.

Water depletion is not modelled at the endpoint using ReCiPe which means it was not highlighted as a potential issue. The South West region is considered to have sufficient rain water for perennial energy crops to thrive (Met Office, 2009; Scholes, 1998; Tuck *et al*., 2006). However, when water depletion is assessed at the midpoint it becomes a potential issue when irrigation is required. This implies that in regions where rain water is insufficient for crop growth water availability could be the main environmental issue for perennial crops.

Harvesting and baling is the main field operation which contributed to the growth of Miscanthus, whereas for SRC Willow it is the use of fertiliser and herbicide. Harvesting is an annual operation for Miscanthus but is done on a 3-year rotation for SRC Willow. The LCI for SRC Willow included higher agro-chemical inputs than Miscanthus based on the information provided by South West farmers. This explains why these inputs were found to contribute more to SRC Willow than in Miscanthus. Other life cycle stages which made notable contributions included drying (when industrial dryers are used rather than natural drying) and irrigation (when insufficient rain falls). Drying and water use are both related to the moisture content (m.c.) of the crop. Where insufficient rain falls it is likely the crops will be less productive resulting in lower yields, and so irrigation is probably required. Conversely where rainfall is high (particularly near to harvest time) the m.c. will increase, and so more drying will be required.

Results from the LCIA are explored in more detail in Chapter 10, where the full life cycle of a bioenergy system is assessed. Comparisons with the production of annual crops such as wheat and oilseed rape are also undertaken. These findings, presented in Chapters 9 and 10, show that both Miscanthus and SRC Willow have much lower impacts than the annual crops they may replace. However, results are based on the impact categories defined in the LCA. Two important environmental impacts which are not considered here are the effects on biodiversity and indirect land use change. Both of these are very difficult to quantify but represent significant challenges with bioenergy systems. Biodiversity and land use change are qualitatively assessed in Chapter 10.

CHAPTER 7. LIFE CYCLE INVENTORY OF A BIOMASS GASIFICATION PLANT

It was identified in Chapter 2 that there is a clear research need for an environmental life cycle assessment (LCA) of a small scale biomass gasification system. Two previous studies focused on large scale combined cycle systems (Carpentieri *et al*., 2005; Mann & Spath, 1997). Currently in the UK there are very few examples of biomass gasification plants in operation. Nonetheless gasification could play an important role in future UK bioenergy production due to its applications to waste management and energy production. The biomass gasification plant (BGP) used in this thesis is believed to be the only one of its type in the UK and therefore offers a unique LCA case study.

This chapter describes the BGP which is used for the LCA and net energy analysis case studies. An overview of the gasification process is presented first followed by the system boundaries. Data on the plant construction and operation has been collected from a variety of sources. A section on data collection therefore follows the overview and system boundaries. The information presented in this chapter forms the basis for the life cycle inventory (LCI) in the LCA study, and the system description in the net energy analysis (see Chapters 8 & 9). The main purpose of this LCI is to identify and quantify the energy, water and materials usage and environmental releases. By providing a detailed life cycle inventory (LCI), this chapter provides an original research contribution.

7.1 OVERVIEW OF THE GASIFICATION PROCESS

This section gives a description of the plant construction, design, and a detailed explanation of its operation. Individual items of equipment referred to below are described in more detail in the data collection section 7.3.

7.1.1 Plant Construction and Design

All biomass gasification plants have similar components. These comprise primarily of:

- Wood (feedstock) handling and supply;
- Gasifier wood feed system;
- The gasifier itself;
- Processing, scrubbing and cooling equipment;
- Gas engine, turbine or similar.
- Buildings which house the above equipment.

The exact design and specification will depend on a variety of factors including: feedstock; size of plant; gasification medium; end-use of producer gas; and so on. Sustainable Energy Ltd (SE) has developed a biomass gasification system which is used as the basis for the system description (see Figure 7-1). The plant construction described below is based on entrained flow gasification (EFG). However, the overall set-up of the plant is broadly similar to other gasification plants.

7.1.2 Wood handling and supply

Wood chip (m.c. of 5%) is received directly from the factory, where the plant is located. The feedstock is chipped into fine particles (like sawdust), and fed into the primary biomass silo, which can store 7-8 tonnes. Since this study is using data directly from the plant, the base case assumes no biomass production, transportation or storage. Other bioenergy systems are likely to require biomass cultivation, transportation, etc. hence these variables are considered in further detail in Chapters 9 and 10.

7.1.3 Gasifier wood feed system

The primary biomass feed screw feeds the feedstock into the main gasification unit, from the primary biomass silo. This operation is driven by two motors and a silo agitator. A discharge rotary valve ensures that the correct amount of feedstock is fed into the main gasification skid unit. Inside the skid unit, feedstock is received into a biomass feed hopper from the outside feed screw (see Figure 7-2). The hopper and feed system consists of a small hopper with agitator and single horizontal auger screw. From here it goes into a biomass feed spiral conveyor, and through a flexible spiral coil screw feeder. This process is driven by a mechanical agitator. By controlling the rotational speed of this screw the feeding rate of the wood chips is controlled. The screw is an increasing pitch auger screw which is driven by a variable speed motor. This feeds the sawdust into an airflow driven by a high pressure rotary gas blower. The hopper provides sawdust loading of 200kg of feedstock per hour.

Sawdust enters the inlet venturi where it passes through 4 valves (a motorised slide valve; an actuated solenoid valve; a motorised air inlet slide valve; and a char rotary valve). This valve system secures that no gas leaks from the gasification reactor.

7.1.4 The Gasifier

The gasifier is started with natural gas, approximately 30 minutes before the running of biomass feedstock (Dr. G. Gallagher, SE, 26th June 2009, personal communication). Actual times may vary slightly depending on the starting and ambient temperature, but 30 minutes is average time given. A burner system is installed to supply and ignite a supplementary gas to fire through the gasifier to heat it up to temperatures to initiate gasification reaction. Specification temperatures are up to 800°C for the reaction initiation. The Nuway MP10 burner is designed to ensure no interruption of the gasification reaction and not to be fouled by biomass particles. The running of the gasification system corresponds with the fuel, so the valves on the gas burner shut when the biomass feedstock starts to be used.

The system used was sized to gasify, under atmospheric conditions, approximately 200 kg of wood per hour (Dr. G. Gallagher, SE, 26th June 2009, personal communication); this gives a total energy input to the gasifier of around 3,600 MJ/hour (1,000 kWh), assuming that the energy content of the wood waste is 18 MJ/kg (ECN, 2009). The gasification conversion efficiency is given as 75%. The reactor is manufactured from (grade 316) stainless steel and insulated with Rockwool. The internal characteristics of the gasifier remain the intellectual property of Sustainable Energy Ltd and therefore are not detailed in this thesis. The gasifier was deigned to achieve the optimum geometry to entrain the biomass particles in a swirling air flow while ensuring sufficient reaction time for gasification to occur.

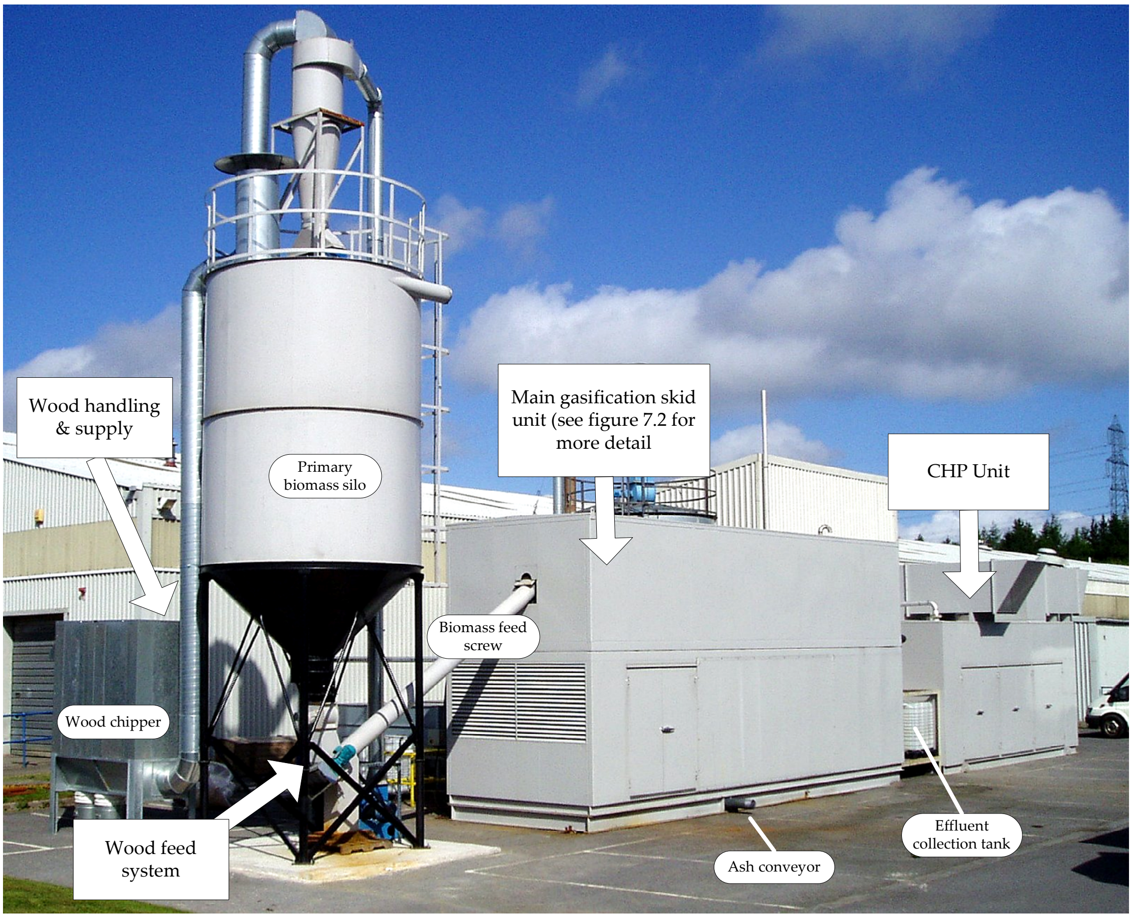


Figure 7-1: Outside view of the biomass gasification system

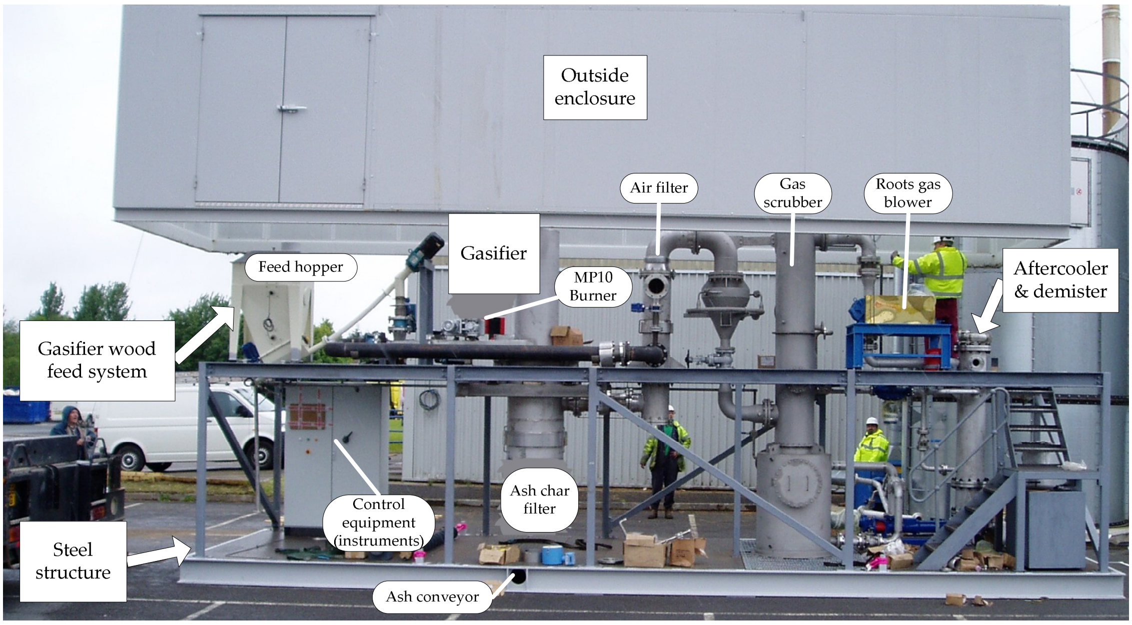


Figure 7-2: Inside the main gasification skid unit

Once the air inlet from the gasifier has been switched to run from the wood feed (the pre-burner has been switched off and the air has been sufficiently pre-heated), particles drop down and wood gas begins to flow through the reactor. Ash and char drop down under the floor, where they are filtered and discharged along an ash conveyor. The screw feeder discharges ash from the bottom of the rotary valves and outside as waste. Ash is collected in a disposal bin and taken to landfill once full. Meanwhile as the gas flows through the reactor, hot gas leaves through the duct (at a temperature of approximately 900°C) and heat is exchanged through the air.

7.1.5 Processing, scrubbing and cooling equipment

When the producer gas enters the scrubber, the temperature of the gas is about 750°C. In order to cool down the gas it is passed through a system of heat exchangers. Gas passes into the Venturi scrubber where it is scrubbed with water, this uses approximately 1 litre/min (see section 7.3.2.9). Gas and liquid are mixed together, with the droplets dumped at the bottom of the scrubber. The gas is then cooled down to just above the water dew point (about 90 °C) in a gas/water cooler and cleaned in a filter. After this the gas is cooled further down to about 30 °C, and condensate is removed. To ensure that droplets produced during the condensation are removed, the gas is then passed through another filter which acts as a demister. A Roots rotary gas blower drives the gas flow.

The main constituents of the produced gas are H_2, N_2,, CH_4, CO, CO_2 and H_2O. The gas is a low calorific gas, meaning that the energy density is low. On a dry basis the lower heating value (LHV) is 5.7 MJ/Nm^3 (Gallagher, 2002). Table 7-1 displays the typical wood gas composition obtained from the gasification plant:

Table 7-1: Wood gas composition (source: Gallagher, 2002)

Gas	%vol./vol.
H_2	9.0%
O_2	1.2%
N_2	57.0%
CH_4	2.0%
CO	15.0%
CO_2	13.0%
Other C_xH_y	0.9%

7.1.6 Outside the Skid Unit

A gas filter is used to further scrub the gas, tars are purged into a barrel and effluents are filtered out using a self cleaning effluent filter. This uses a wedge wire mesh, with the effluents collected in an effluent collection tank. Several parts of the heat exchanger equipment are also located outside the back of the skid unit. These include a water cooler, a dry air cooler, valves and pipes. Most of the wood handling equipment and the gas engine are also outside the main skid unit (see Figure 7-1).

7.1.7 CHP unit

The CHP unit is housed in a separate housing (see Figure 7-1) which contains the gas engine, heat recovery equipment, an electrical generator, control equipment, and a flue for conveying exhaust gases (see Chapter 2 section 7). Producer gas exits the main skid unit and is supplied to the gas engine through piping. The gas engine powers the electrical generator which creates electricity for use either locally or fed back into the grid. Simultaneously the CHP heat recovery system both space heating and hot water for the building as required.

Electrical efficiency is 34% and outputs from the system are as follows (Dr. G. Gallagher, SE, 25th June 2009, personal communication):

- Net electrical output = 230 kW (828 MJ/hr)
- Thermal (heat) output = 500 kW (1,800 MJ/hr)

7.1.8 Buildings

This plant was designed in such a way that it could, if required, be transported to another site. Consequently, the buildings used are not permanent structures and could be lifted onto a lorry (see Figure 7-2). The main gasification skid unit is housed in a stainless steel structure and enclosure. Similarly, the CHP unit supplied by Cogenco also has a stainless steel outside enclosure.

7.2 SYSTEM BOUNDARY

Identifying the system boundary is an important part of any LCA or net energy analysis study (see Chapter 3). Figure 7-3 provides a useful overview of the system boundary. Both the plant construction and plant operation were included in the boundaries and are described separately below. The starting point for the operation of the plant is the collection of wood waste from the factory, with the end point being the production of both renewable electricity and heat.

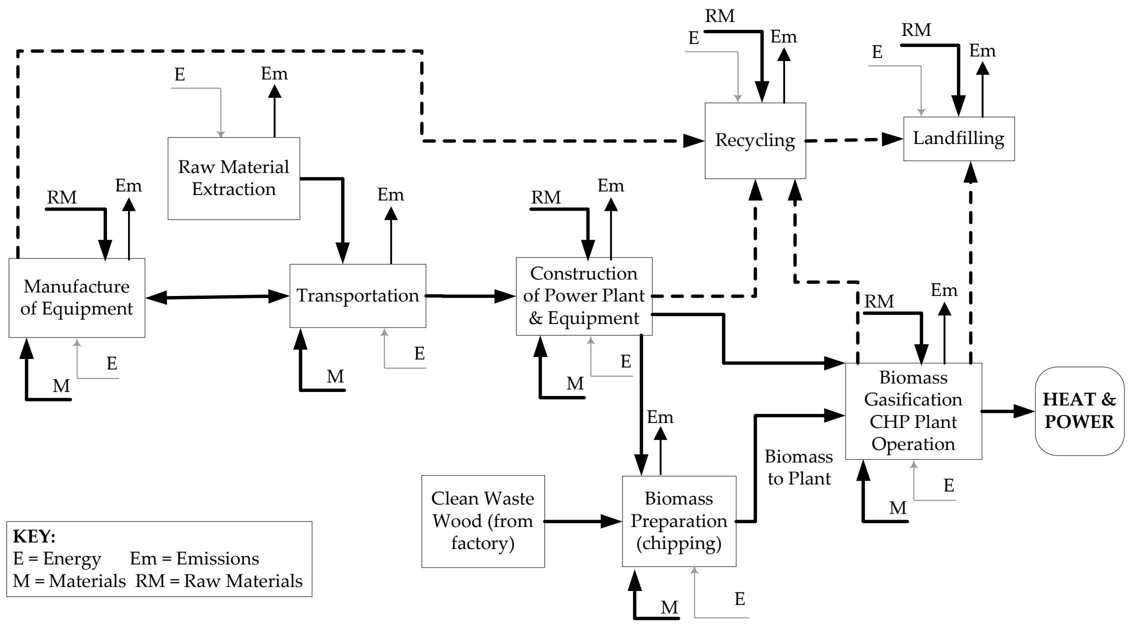


Figure 7-3: Overview of the system boundary for the biomass gasification plant construction and operation

7.2.1 Plant construction

All items of equipment in the plant have been included in the plant construction system boundary (see Figure 7-4). The equipment used in the plant is described in more detail in the data collection section (see section 7.3.1) and Appendix G.

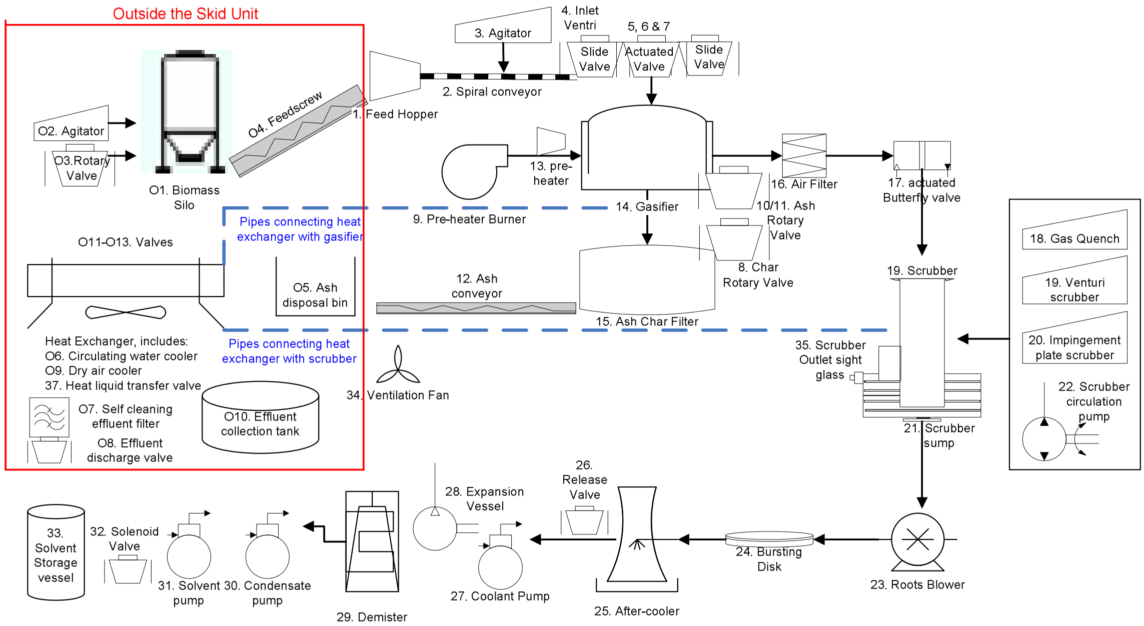


Figure 7-4: Main items of equipment used in the gasification process (not to scale)

Manufacturing of the equipment is included, which also takes account of the raw materials extracted, transportation and energy used in manufacturing. Primary data was obtained from a variety sources for the type and amount of materials used in each item of equipment (see section 7.3.1 for further details). Secondary data from the Ecoinvent database was used for the upstream processes associated with each type of material (Swiss Centre for Life Cycle Inventories, 2009). The energy used in manufacturing was either obtained directly from the equipment supplier or an industry average was taken from Ecoinvent. See data collection in section 7.3 and Appendix G for more details. In addition to the gasification process equipment, the gas engine, instruments, outside enclosure and the steel structure are also included in the study.

7.2.2 Plant operation

All of the main operational processes have been included in the plant operation system boundary. The boundary starts when wood is collected from the factory and fed into wood chipper to be processed into sawdust, and ends with heat and power generation. Throughout the system various material and energy inputs are required to operate the plant. These include natural gas, electricity, water, lubricating oil and air. Concurrently, several outputs are released from the system, some of which are desired products, i.e. combined heat and power generation, and others are undesired, i.e. emissions and wastes. Figure 7-5 summarises the main inputs, processes, outputs and emissions from the plant operation.

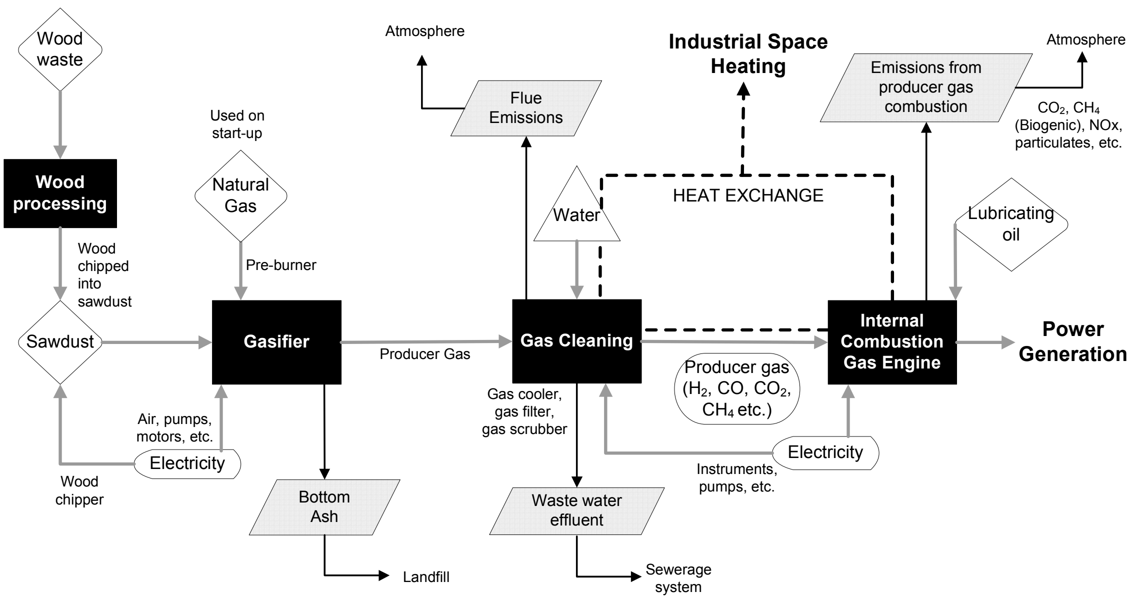


Figure 7-5: Simplified display of biomass gasification CHP plant operation with main inputs, processes, outputs and emissions

7.3 DATA COLLECTION

7.3.1 Plant Construction

SE supplied a schedule of the equipment, instruments and the electrical specifications and cabling contained within the plant. For equipment, the information provided included the name of the item, a description, and the manufacturer. For instruments, a similar schedule was provided along with model numbers (where available). The electrical specifications provided details of electrical components and cables used within the plant. However it was decided to leave the electrical specifications outside of the system boundary due to insufficient inventory data being available. Due to the number of items, further details of the life cycle inventory are included in Appendix G.

From the data provided, three site visits, and a significant amount of further research, a life cycle inventory (LCI) was generated using the following methods (see Figure 7-6):

1) Contact was made with the manufacturer of the equipment/instrument to ask for the type of materials used in each item, weight of materials, and the manufacturing processes used. For several items this information was provided directly by the manufacturer via an email, telephone call or company literature. This primary data was input into the LCI. Where this information could not be provided directly, it was necessary to calculate or estimate materials used in each item (see 2 to 4).

2) Using engineering diagrams and list of materials it was possible to calculate or estimate materials used. These were available for most items either directly from the company, or from suppliers. In many cases, this product detail is easily accessible from manufacturer's websites. In some cases the manufacturer provided the total weight of the item, but a breakdown for each material (by weight) was not given. For most items, it was possible to obtain an engineering diagram and a list of materials. The diagrams provide dimensions and relative sizes of each material. From this the weight of materials was estimated by researching material densities. Other items, such as the Gasifier, scrubber, SE provided

the CAD drawings. From these drawings the total weight of the materials (which were mostly grade 316 stainless steel) were calculated.

3) Where data could not be supplied by the manufacturer, the alternative method was to find a similar product produced by another company, or use a similar product in SimaPro, the materials used could then be estimated. This method was only used for one item of equipment (Scrubber outlet sight glass) as indicated in Appendix G.

4) Where data could not be obtained from the manufacturer or similar product, further research was needed. Options for further research included contacting the company again; weighing the item and assessing materials used; measure item and estimate weight based on density; find similar items, or further research item. As a last choice the item could be left outside the boundary of LCA (beyond scope), but fortunately this was not required for any items.

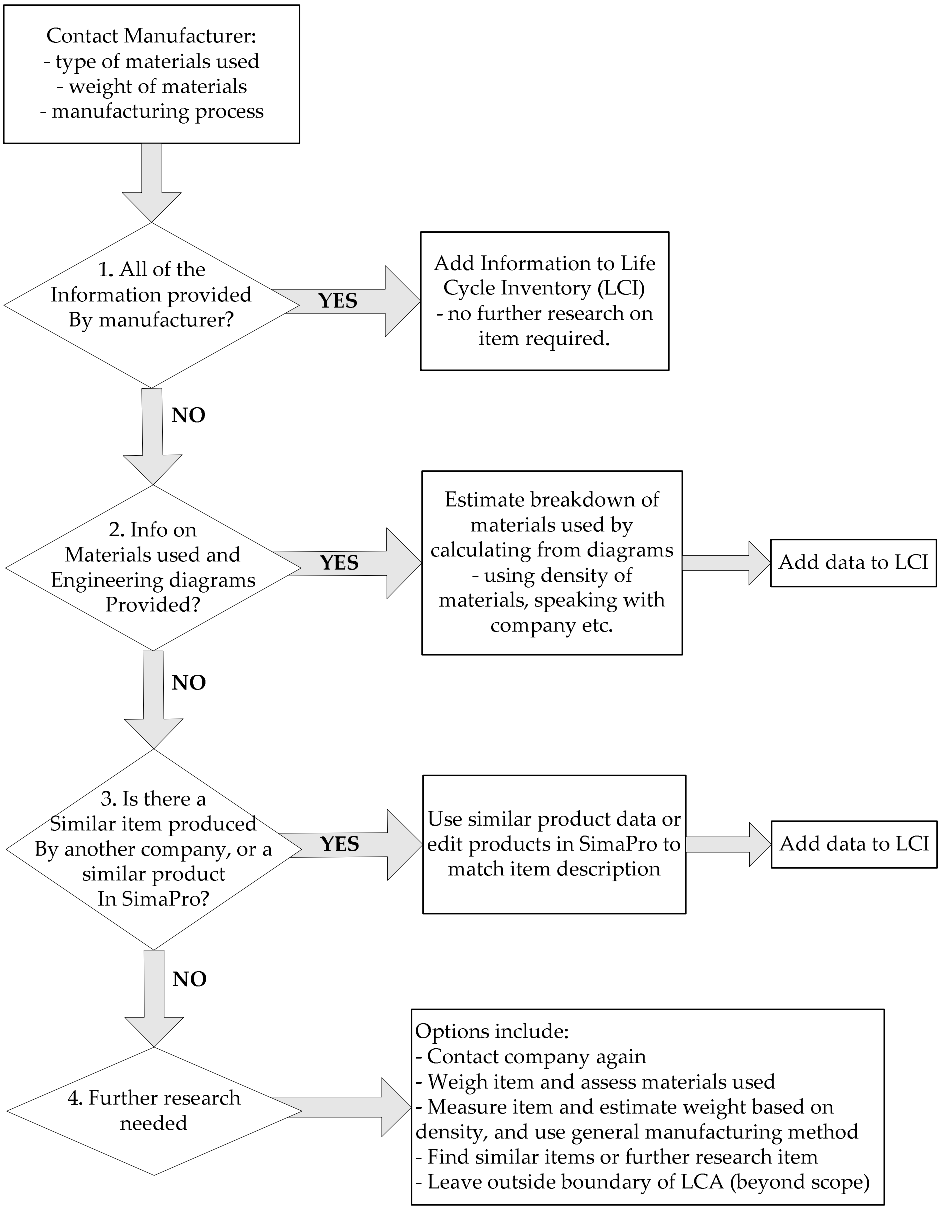


Figure 7-6: Plant construction data collection methods

Due to the number of items of equipment, the inventory has been grouped together for convenience and summarised in Table 7-2. Further details of the LCI for plant construction are provided in Appendix G.

Table 7-2: Groups of items of equipment used in Biomass Gasification Plant

Name	Description
Outside enclosure	Steel and coating used around the outside of the buildings.
Steel structure	Steel beams, stairs and flooring used for structure of skid unit.
Biomass silo	Provides storage and supply of wood chips (sawdust), located outside the main skid unit.
Feed hopper	Where the wood chips first enter the main skid unit and feed into the gasifier.
Valves	A series of valves used to control the flow of feedstock into the gasifier, and producer gas around the system.
Pre-burner	Used to pre-heat the gasifier.
Gasifier	Main part of the gasifier where the gasification reactions occur.
Ash disposal	Lower part of the gasifier which collects the ash for disposal.
Scrubber	Producer gas is mixed with water to cool the gas down and clean the gas to remove potential contaminants from the gas.
Pumps & blower	These provide the mechanical energy for the gas flow around the system.
Aftercooler & demister	Used to cool the producer gas and remove condensate.
Solvent handling	Effluent which is removed from the gas in the scrubbing process is collected outside the skid unit.
Heat exchanger	Captures the useful heat energy from the system to use as CHP.
Instruments	Used to control the operation of the plant.
Outside the skid	Pressure relief valve, temperature control valve and gas drop valve.
Gas engine	Utilises the producer gas for electricity and heat generation.

Most materials and processes used in each item of equipment have LCI data available in the Ecoinvent database (Swiss Centre for Life Cycle Inventories, 2009). For example, grade 304 stainless steel (304 ss), mild steel, copper, aluminium, iron, brass, etc. all have detailed LCI data available. Reliance has therefore been placed on the Ecoinvent database for the LCI data for almost all materials and processes. The main exception to this is the most common steel used in construction of the plant [grade 316 stainless steel (316 ss)]. There was no data available in the Ecoinvent data for 316 ss, therefore this had to be further researched. The British Stainless Steel Association (BSSA) was contacted to establish the production methods of UK stainless steel. Additional data was also obtained from the International Stainless Steel Forum (ISSF), see Appendix G for further details.

7.3.2 Plant Operation

An overview of the plant operation is given in section 7.1. More detail is now presented along with the main assumptions used to model the operation of the plant, and compile the life cycle inventory. This also aides the understanding of the equipment required in the construction of the plant. The net electrical output of the BGP is 230kWh (828MJ) per hour and the thermal output has a maximum potential of 500kWh (1,800MJ) per hour. A review of currently operation biomass gasification plants showed that the average annual operating hours is 2,500 (Knoef, 2005). The following subsections describe the data used.

7.3.2.1. Plant construction

The inventory from the construction of the plant was scaled down to give the amount of plant required to produce 1 MJ of electricity. The total amount of electricity produced over the 20 year lifetime of the plant was calculated as 41,400,000MJ (11,500,000kWh), based on 2,500 operating hours a year and a net electrical output of 828MJ/hr (230kW). This gave the total BGP per 1MJ of electricity as 2.415×10^{-08} (i.e. 1/41,400,000).

7.3.2.2. Feedstock supply

Woodchip is produced onsite, as a by-product from a furniture factory. As this study is focussed on bioenergy production and use, the factory is outside the system boundary. The main input to the woodchip is assumed to be the energy required in wood chipping. If the feedstock was grown specifically for the bioenergy system, then carbon dioxide (CO_2) fixed in the wood would also be included. However for waste this is not the situation and so CO_2 fixation is left outside the boundary for the base case, this is instead assessed in Chapter 10.

Wood is a naturally grown material; it's shape and properties do not always suit industrial production processes. Consequently, many production processes throughout the wood processing supply chain generate industrial residual wood. For this study it was therefore considered appropriate to use an average of UK industrial wood waste. Average wood production over 10 years from 1996-2005 was 7,590 thousand green tonnes per annum for softwood, and 661 thousand green tonnes per annum for hardwood (Forestry Commission, 2006). The carbon content varies slightly for different types of wood, softwood ranges from 47.21% to 55.20% (average 51.05%), whilst hardwood ranges from 46.27% to 49.97% (average 48.41%) (Lamlom & Savidge, 2003). Table 7-3 shows that the average bulk density of softwood is 169 kg/m^3, and hardwood is 239 kg/m^3 (Forestry Commission, 2006).

Table 7-3: UK softwood and hardwood production, bulk density and carbon content

	Softwood	Hardwood	UK Total	UK Mixed
Average production 1996-2005 (thousand green tonnes per annum)	7,590	661	8,251	-
Average production (% of UK total)	92%	8%	100%	-
Average bulk density (kg/m^3)	169	239	-	174.61[a]
Average carbon content (%)	51.05	48.41	-	50.84[b]

The 'UK mixed' column of Table 7-3 represents the calculated UK average bulk density and carbon content of industrial residual wood. This was calculated by taking the % of UK production and applying it first to the average bulk density, and then to the carbon content:

a) UK mixed average bulk density = 169 * 92% + 239 * 8% = 174.61 kg/m^3

b) UK mixed average carbon content = 51.05 * 92% + 48.41 * 8% = 50.84 %

For wood used as fuel, the water content of the wood is very important because it changes the density and the heating value in wide ranges (see section 2.1.4.1). To overcome this problem, the functional unit (for wood) in this study is largely given as m^3, since the volume remains more or less constant with changing water content.

7.3.2.3. Wood chipping

Wood chipping takes place on site at the gasification plant. The chipper is powered by a 35kW motor; additionally a 5kW motor is used for feeding the wood. The chipper consists of unalloyed plates and weighs 2 tonnes. Its service life is estimated as 30,000 service hours or 100,000m^3 of wood. The wood chipper also contains 5 litres of lubricating oil which needs to be changed every 4,000 service hours; or 13,000m^3 of wood. Energy consumption is 27MJ/m^3 of wood, and uses UK grid electricity.

Direct emissions to air are not caused by the wood chipping process, except wood dust. However, it was not possible to obtain data on wood dust emissions. The indirect emissions from its use therefore arise from the use of electricity. In the sensitivity analysis, wood chipping by a diesel fuelled wood chipper is assessed.

7.3.2.4. Wood feed system

Chipped wood (sawdust) is fed into the system as described in section 7.1.3. This part of the operation requires electricity to run the motors and pumps. There are no direct emissions associated with the wood feed system.

7.3.2.5. Pre-burner

The MP10 burner is 150kW which fires for approximately 30 minutes each start up (Dr. G. Gallagher, SE, 26th June 2009, personal communication). Therefore it is calculated that 270MJ (75kWh) of natural gas is burnt each time the plant is started. The plant is likely to be shut down and restarted twice a week on average, so 27,000MJ (7,500kWh) are assumed to be consumed each year, assuming 50 working weeks per year.

In order to convert this to the functional unit of 1MJ of electricity (and 1 Nm^3 of producer gas), the following assumptions were used:

- 828 MJ/hr (230 kW) net electrical output (see section 7.1.7);
- Each 1MJ of electricity requires 0.519 Nm^3 of producer gas (1kWh of electricity requires 1.87 Nm^3 of producer gas);
- There are 2,500 plant operating hours per year;
- Therefore, 10.8MJ (3kWh) of natural gas required per operating hour, i.e. 27,000 / 2,500 (or 7,500 / 2,500);
- This gives 0.01304MJ of natural gas required per MJ of electricity produced (i.e. 10.8 / 828), which is equivalent to 0.0252MJ of natural gas per Nm^3 of producer gas

Data for the impact of burning natural gas is obtained from the Ecoinvent database. Natural gas burned in the MP10 burner is modelled based on data from natural gas burnt in an industrial burner. The data for1 MJ of gas burnt by the MP10 burner are shown in Appendix G. Natural gas at the consumer takes into account the extraction, long distance piping, and distribution of the gas. It takes an average of the imported mix of gas and takes account of network losses and leakages. The emissions to air are based on the average composition of natural gas.

7.3.2.6. Gasifier

Feedstock fed into the gasifier is accounted for in the inventory under feedstock supply and wood feed system. Heat is also supplied to the gasifier, which is accounted for in the pre-burner.

The only other input is electricity used to control the gasifier operation, wood input flow, and the ash disposal system (see section 7.3.2.11).

Producer gas and heat are the main outputs from the gasifier. At the exit of the gasifier, the main desired product in the producer gas is the permanent gas (H_2, CO, CH_4, CO_2, and N_2) (IEE, 2007). Heat produced is also a useful product which is utilised in the CHP plant. There are also undesired by-products which include: particulate matter, dust, soot, and organic pollutants (e.g. tars, or polycyclic aromatic hydro carbons (PAH)) (IEE, 2007). It is also possible that by-products will include inorganic pollutants, such as alkali metals (Lieuwen *et al*., 2010). However, the wood used in this case study (and in general) has very low amounts of such metals.

7.3.2.7. Ash collected

Another important emission from the gasifier is ash which falls to the bottom of the gasifier and is removed. The mineral content in the fuel that remains in oxidized form after complete combustion is usually called ash (Rajvanshi, 1986). The ash content of a fuel and the ash composition can have a major impact on the gasifier. According to Rajvanshi (1986) ash can interfere with the gasification process in two ways:

- It fuses together to form slag which can inhibit the downward flow of the biomass feed.
- It can shelter the points in fuel where ignition is initiated and therefore lowers the fuel's reaction response.

Ash and tar removal are therefore very important for the continuous operation of a gasifier. It was not possible to obtain primary data from the plant on the amount of ash produced. According to the literature survey and given the typical composition of wood, the amount of ash collected at the bottom of the cyclone is taken as (Swiss Centre for Life Cycle Inventories, 2009):

- Softwood = 8.491 g/kg
- Hardwood = 4.850 g/kg

Taking the UK mixed wood (see section 7.3.2.1) the average amount of bottom ash collected is assumed to be 8.199 g/kg (i.e. 8.491 * 92% + 4.850 * 8%). Consequently there will be 1.431kg of ash per m^3 of wood; this equates to just over 0.8% of ash generated per unit of wood input. This is comparable to a DTI study which found ash produced was 0.9% by weight (McLellan, 2000). The composition of ash was taken as the average for wood from the Phyliss database (ECN, 2009), and shown in Table 7-4.

Ash is assumed to be disposed of to landfill at a distance of 20km from the BGP. This requires the use of a lorry to dispose of just over 4 tonnes of ash per year. Due to the uncertainties with the amount of ash collected and its composition, different scenarios are assessed in the sensitivity analysis.

Table 7-4: Average composition of ash from wood (source: ECN, 2009)

Element	Symbol	mg/kg db
Organic Carbon	-	600
Sulphur	S	23,800
Silicon	Si	121,000
Calcium	Ca	225,000
Magnesium	Mg	35,900
Potassium	K	33,000
Sodium	Na	10,000
Phosphate	P	19,800
Aluminium	Al	54,500
Iron	Fe	17,000
Copper	Cu	124
Zinc	Zn	559
Nickel	Ni	123
Chromium	Cr	243
Lead	Pb	316

7.3.2.8. Gas scrubbing

Having exited the gasifier, the gas is subsequently cleaned to remove contaminants, and the heat is used in the heat exchanger. Gas cleaning fulfils the purpose of providing constant gas qualities for the gas engine. It also has the task of de-dusting the producer gas as well as ensuring suitable purity regarding tar load. Wet gas cleaning is purification of the producer gas by means of liquid scrubbing agents in the scrubber system. The cleaning effect is brought about by the adherence of the contaminants to and the dissolving of the contaminants by washing agents. This kind of gas cleaning additionally fulfils the function of gas cooling because of the heat exchange between the producer gas and the washing agent due to the intensive contact and the heat removal through heat extraction via suitable heat exchangers.

In this case study water is used as the washing agent; other options include water/oil (e.g. biodiesel RME) emulsions, condensate and various hydrocarbons (IEE, 2007). After wet gas cleaning the producer gas can be used for combined production of heat and power, e.g. on basis of gas engines, gas turbines or fuel cells as the conversion unit.

Primary data on the composition of wastewater could not be obtained directly from the plant. Therefore a literature review was performed to obtain inventory data for wastewater. Two studies were found and considered to be appropriate for inclusion in the LCI. For the base case, a study by Lunds University in Denmark on the toxicity of wastewater generated by the gasification of wood chips was used (Lunds Universitet, 2003). Table 7-5 displays the substances included in waste water inventory, the other study is assessed in the sensitivity analysis.

Table 7-5: Substances included in waste water inventory (source: Lunds Universitet, 2003)

Group	Substance	Concentration in waste water (g/l)
Simple alcohols	Methanol	3
	Ethanol	Low (less than 10 mg)
Carboxylic acids	Acetate	30
	Formic acid	4
Simple phenols	Phenol	0.85

7.3.2.9. Water use

Water is used in both the scrubbing system and the heat exchanger. Water in the scrubbing system is re-circulated in a circuit at approximately 16m^3/hr or 266l/min. From this approx. 0.06m^3/hr is purged from the scrub system and released as foul water. The same amount is therefore required as a clean water input to keep the system in balance. Water in the gas cooler heat exchanger is closed circuit circulating at 1m^3/hr or 16l/min. This is sealed so does not require further water input (Dr. G. Gallagher, SE, 2nd July 2009, personal communication).

Water use within the gasification system is used in 4 stages, summarised as follows:

- water in (for scrub system make up of rejected water);
- water in the gas cooling heat exchange (sealed);
- CHP plant exhaust heat exchange water (sealed);
- turbo intercooler (sealed)

Only scrub water is refilled and rejected though out normal operation. 60 litres per hour are released to the drain (i.e. 1 litre per minute). This same amount is therefore also required as an input to the plant. The inventory data used for the supply of water is taken as the global average from Ecoinvent, which has an energy requirement of 0.390kWh/m^3.

7.3.2.10. Emissions from producer gas combustion

Essentially all carbon contained in producer gas components will end up as carbon dioxide when the producer gas is burned, provided that there is sufficient air and mixing (Lieuwen *et al*. 2010). Producer gas components contributing to CO_2 emissions include carbon monoxide, hydrocarbons, and the carbon dioxide itself. It was not possible to obtain primary data from the plant on the emissions from producer gas combustion. In order to model this output the following methodology as used in Ecoinvent was applied (Jungbluth *et al.*, 2007).

Emissions relating to syngas combustion are considered according to the composition of the syngas:

- CO is completely converted completely to CO_2;
- CO_2 does not react in the combustion process and is therefore emitted as such;
- CH_4 and C_nH_m altogether are considered as 'natural gas' and described according to the emissions of the process 'natural gas burned in industrial furnace > 100kW (emissions only)' see Appendix G;
- H_2 is converted to water.

7.3.2.11. Electricity use in the plant

Electricity is consumed in the plant to provide power for pumps, motors and control equipment. The parasitic load is given as 25kW, which is required to run the plant during operation. This provides power for the Roots blower and the motors used in the wood feed system, gasifier, scrubber, and heat exchanger. There are also several pumps used in the plant which also require electricity. Control equipment is used throughout the plant to monitor gas flow, pressure, and temperature. The CHP unit also runs a computer system which allows the plant to be monitored remotely.

When the plant is started up it is reliant on UK Grid electricity for power. However, once it is operating at normal capacity the plant uses its own generated renewable electricity to satisfy the parasitic load. Approximately 10% of the plant's electricity comes from the UK grid. To model this it was necessary to establish a specific grid 'electricity mix', typical of the UK. Data was obtained on the total electricity supplied by each fuel source for all generating companies in 2008, see Table 7-6 (DECC, 2009a).

The impacts of UK electricity were modelled in the life cycle assessment software package SimaPro, which models the upstream impacts of energy production, including, for example, oil extraction and refining. The fuel inputs and electricity outputs in the UK for the year 2008 were taken from the Digest of UK Energy Statistics (DUKES) (DECC, 2009a). The full range of impacts for the production of UK grid electricity was estimated for each impact assessment methodology.

Table 7-6: Data used for modelling the potential environmental impacts of UK electricity production (source: DECC, 2009a; Swiss Centre for Life Cycle Inventories, 2009)

Inputs from Technosphere	GWh	%	Notes
Nuclear, at power plant	47,673	13.0	European average production.
Coal, at power plant	118,941	32.3	European average production.
Hydropower, at natural flow power plant	5,136	1.4	Global average production.
Hydropower, at pumped power plant	4,075	1.1	Global average production.
Wind power, at power plant	7,114	1.9	Global average production. Assumed all renewable non-thermal sources use wind.
Oil, at power plant	5,304	1.4	UK average production
Natural gas, at power plant	173,502	47.2	UK average production
Electricity from waste	9,369	2.5	Assumed all renewable thermal sources use waste for fuel.
Coke oven gas, burned in power plant	2,218	0.6	Used coke oven gas in model, but also some other sources.
Total	**367,961**	**100%**	

By modelling this in SimaPro, account is taken of all the material and energy demands to produce 1 GWh of electricity for each fuel source. It also takes account of the associated emissions and releases with each type of electricity generation. This can then be reduced to a functional unit of 1 MJ of electricity produced via the UK grid. Most of the inventory data is for the UK and was obtained from the Ecoinvent database. The exceptions to this were electricity produced from coal and nuclear, which took an average of European production, and electricity from wind power which took a global average.

7.3.2.12. Lubricating oil used in gas engine

Lubricating oil is used in several moving parts, but primarily in the gas engine, and in the wood-chipper. The gas engine contains 27 litres of lubricating oil and should be replaced every 1,500 operating hours or every six months, according to the manufacturers' recommendations. Other lubricating oil in the plant is estimated as 5 litres per year. The wood chipper also contains 5 litres of lubricating oil, which needs to be changed every 4,000 hours (i.e. approximately 3 litres per year). Production of the lubricating oil and transportation to the BGP are included in the LCI. Disposal of used lubricating oil has not been included in the study as insufficient data could be obtained.

7.4 SUMMARY

A novel life cycle inventory (LCI) has been presented in this chapter and Appendix G, representing original research. LCI data on the biomass gasification process has been established for the material and energy inputs, as well as the emissions to air, water and soil. This data includes the main inputs to the plant such as wood waste, water, electricity, natural gas, lubricating oil, and the manufacture of equipment. Primary outputs include electricity and heat generation, direct emissions such as producer gas combustion, ash, waste water effluent, and natural gas combustion; and indirect emissions such as those arising from the use of UK grid electricity.

A variety of data sources are required to obtain sufficient information to perform both the LCA and net energy analysis. This LCI data provides the detail required for the biomass gasification system studies in chapters 8, 9 and 10. Primary data were obtained for the plant construction and operation where possible, but it was also necessary to use secondary data. Due to the vast amount of underlying LCI data for each input, reliance is also placed on the inventory database Ecoinvent.

The work presented in this chapter provides a new contribution to knowledge due to the LCI data obtained. This is clearly demonstrated in the gasification plant construction data as this is the only known BGP of this type in the UK. For the main items of equipment over 30 companies were contacted and data obtained on over 50 items. For the plant operation not all of the data could be obtained directly from the BGP. Where there were gaps in the data further research has been performed to find alternative data sources. By bringing together the various aspects of plant operation, such as energy use, water use, feedstock requirements, emissions, etc., a unique LCI for biomass gasification has been completed.

CHAPTER 8. LIFE CYCLE ASSESSMENT OF A BIOMASS GASIFICATION PLANT

This chapter describes the life cycle assessment (LCA) study undertaken on the biomass gasification plant (BGP). By using a novel LCI for a biomass gasification system and applying a new impact assessment methodology, this LCA evidently provides valuable original research. Important results established include the main potential environmental impacts of concern with biomass gasification. These are shown to include fossil fuel and metal depletion, and potential damages to human health through greenhouse gas, particulates, and other emissions. The Findings from this chapter were originally presented at the 19th SETAC LCA Symposium held at the University of Poznan, Poland in March 2010. Further results were also published at the Bioten conference held in Birmingham in September 2010 (see Appendix A).

8.1 GOAL AND SCOPE

The main goal of this study is to assess the potential environmental impacts, on a life cycle horizon, of the production of heat and power through biomass gasification. It is intended that the results generated can be used to understand the relative impacts of different aspects of the biomass gasification plant's (BGP) construction and operation. Hence, the objective is to highlight the most important factors that affect the environmental load of the BGP. Subsequently in Chapter 10, the results are used to compare the environmental performance of biomass gasification to other forms of heat and power generation.

8.1.1 Function and functional unit

Renewable electricity and heat from biomass gasification is the main function of the system studied. A secondary function of the system is waste management. To achieve this, waste wood is put through a gasification process, the producer gas created is then scrubbed and cleaned and used in an internal combustion gas engine. Electricity that is generated by the gas engine is either used on-site for own consumption or supplied to the electricity grid. The heat produced by the process is used for heating industrial buildings. The functional unit of the plant operation study is 1 MJ of energy produced. As both electricity and heat are produced, the environmental impacts of the system can be allocated using different allocation methods (see section 8.3.3). For the plant construction study the interim functional unit is one BGP.

8.1.2 System Boundary

The system boundary described in the previous chapter is used as the basis for the LCA study. It is necessary to describe and display what is included in the LCA, so it can be understood where the boundaries of the system are set. The approach of this LCA was to first build up the life cycle inventory (LCI) for the construction of the BGP, followed by the LCI of the plant operation, both of which are described in detail in Chapter 7.

8.2 LIFE CYCLE INVENTORY (LCI)

The main purpose of the LCI is to Identify and quantify the energy, water and materials usage and environmental releases (e.g. air emissions, solid waste disposal, waste water discharges) (Curran, 2006). Data used in this study are presented in Chapter 7 and Appendix G, therefore only a brief summary is given here.

8.2.1 Plant Construction

Plant construction inventory data (see Chapter 7) items have been grouped together into nine groups. This is to make the data analysis more convenient by placing smaller items into their respective part of the gasification process. Nine data points is also more appropriate given the amount of information to be displayed. Table 8-1 summarises the nine groups chosen:

Table 8-1: Plant construction inventory: groups of items for LCIA, main items and predominant materials

SimaPro Name	Groups of items included	Main items	Predominant materials
1. Outside enclosure	Outside enclosure	External walls, roof and doors	Stainless steel, metal coating.
2. Steel structure	Steel structure	Steel beams, stairs and flooring	Stainless steel.
3. Wood feed system	Biomass silo; Feed hopper & valves	Wood chipper, Silo, feed hopper,	Mild steel, zinc alloyed steel, metal coating.
4. Gasifier	Pre-burner; Gasifier; Ash disposal	Pre-burner, gasifier and ash disposal system	Stainless steel, mild steel, rock wool insulation.
5. Gas scrubber	Gas scrubber; Pump & blower	Scrubber, pumps and air blower	Stainless steel, aluminium, cast iron, mild steel, flouroelastomer.
6. Aftercooler & demister	Aftercooler & demister; Solvent handling; Items outside the skid	Gas aftercooler, coolant pump, expansion vessel, demister, condensate pump.	Stainless steel, aluminium, cast iron, mild steel, polyethylene.
7. Heat exchanger	Heat exchanger; Pipes	Water cooler, dry air cooler, pipes, ventilation fan, control valves.	Stainless steel, aluminium, zinc alloyed steel, copper, polyethylene.
8.Instruments	Switches, sensors, flow meters, temperature gauges, pressure gauges, transmitters, etc.		Various small amounts
9. Gas engine (CHP Unit)	Internal combustion engine		Reinforcing steel, low-alloyed steel, stainless steel, copper, aluminium, iron-nickel-chromium alloy, polyethylene, ployvinylchloride

8.2.2 Plant Operation

During the operation of the plant the net electrical output is 828MJ/hr (230kW). There is also the potential to utilise up to 1,800MJ/hr (500kW) of thermal (heat) output per hour. Utilising this thermal output depends on there being sufficient demand for useful heat. The results presented in section 8.3.2 assume that this heat is not used and is emitted as waste heat. However different heat demand scenarios are discussed in section 8.3.4 and assessed in further detail in the net energy analysis in Chapter 9.

Table 8-2 summarises the main inputs for one year of plant operation. The full BGP operational inventory data are described in Chapter 7.

Table 8-2: Main biomass gasification plant operational inputs

Input	Amount	Total per year	Comments
Waste wood	200 kg/hr	500 tonnes	This includes electricity consumption from UK grid for pre-processing.
Electricity	90 MJ/hr	225,000MJ (62,500kWh)	Approximately 10% comes from UK grid, with remainder produced internally.
Natural gas	270 MJ per start-up	27,000MJ (7,500kWh)	Assumed 100 start-ups per year.
Water	60 litres/hr	150,000 litres	Consumed to replace scrub water.
Lubricating oil	Various	62 litres	Consumed to change used lubricating oil.

8.3 LIFE CYCLE IMPACT ASSESSMENT

The third stage of the LCA study was to carry out a life cycle impact assessment (LCIA) based on the LCI outlined in the previous chapter. An assessment of all impact categories was made using the approach outlined in Chapter 3 section 6. The results presented first assess the impacts associated with the construction of the biomass gasification plant (BGP). Next the plant operation is considered, which incorporates the results from plant construction. For both plant construction and plant operation results are presented using ReCiPe (endpoint) to highlight the main contributions and the key issues. These are then verified using Eco-Indicator 99. The impact categories of environmental concern are then assessed in more detail using ReCiPe (midpoint). The 'hierarchical' viewpoint (denoted 'H') has been used for the main results (Goedkoop *et al.*, 2009). Results were also produced for the egalitarian and individualist viewpoints, but have not been included in this thesis.

8.3.1 Plant Construction LCIA

The functional unit is taken as the production of one biomass gasification plant (BGP). This includes all raw materials, equipment, transportation and energy needed to produce the BGP described in Chapter 7 and grouped together into 9 groups as described above.

8.3.1.1. ReCiPe (endpoint)

Figure 8-1 portrays the characterised results for the construction of the biomass gasification plant. It shows that the outside enclosure, steel structure and gas engine make particularly large contributions towards all impact categories. This is mainly due to the high use of metals, particularly steel, in these parts of the plant. In all impact categories the outside enclosure, steel structure and gas engine together contribute to over 60% of the impact. Other parts of the plant, such as the aftercooler and demister, make almost no contribution to each category. To understand why, further analysis of each part is required.

Starting with the gas engine, the main materials used in its construction are different types of steel, copper, and aluminium. Sheet rolling of steel and aluminium, and welding are the main processes required to manufacture the engine. The materials are also transported from all over the world via freight ships and lorries. Both the outside enclosure and the steel structure are made almost entirely from stainless steel, with a small amount of metal coating. Hot rolling of steel is required along with welding to produce and construct the structure and enclosure of the building. Construction of the gasifier (which is made almost entirely from grade 316 stainless steel) contributes between 5 and 10% to each impact category. It therefore becomes apparent that the use of metal in the plant construction is the biggest contributor to all environmental impact categories.

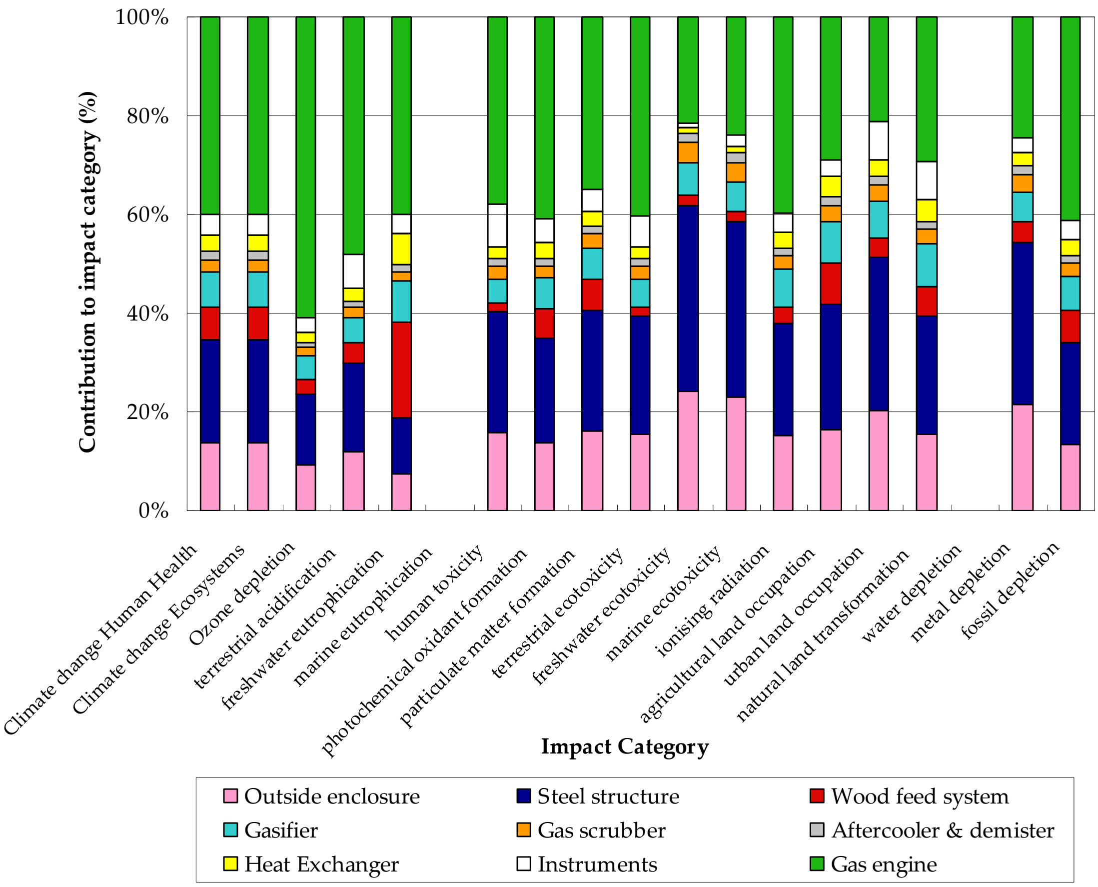


Figure 8-1: Characterised Data for Gasification Plant Construction – ReCiPe endpoint (H)

Characterised data is useful to identify the parts of the plant which contribute to each impact category. However, the characterised data only looks at the percentage contribution to each category. It does not examine the significance of the categories themselves with respect to total emissions of the substances in Europe for which the normalised results must be studied. The normalised results (see Figure 8-2) show the categories in the plant construction with the largest relative impacts.

Figure 8-2 illustrates that fossil fuel depletion is the most important issue associated with plant construction when the normalised impacts are considered. Both climate change impact categories along with particulate matter formation are also key issues due to their correlation with fossil fuel use. Human toxicity is a potential issue because of the release of various toxic substances during manufacture of different equipment. Metal depletion is the other issue of concern, as previously discussed.

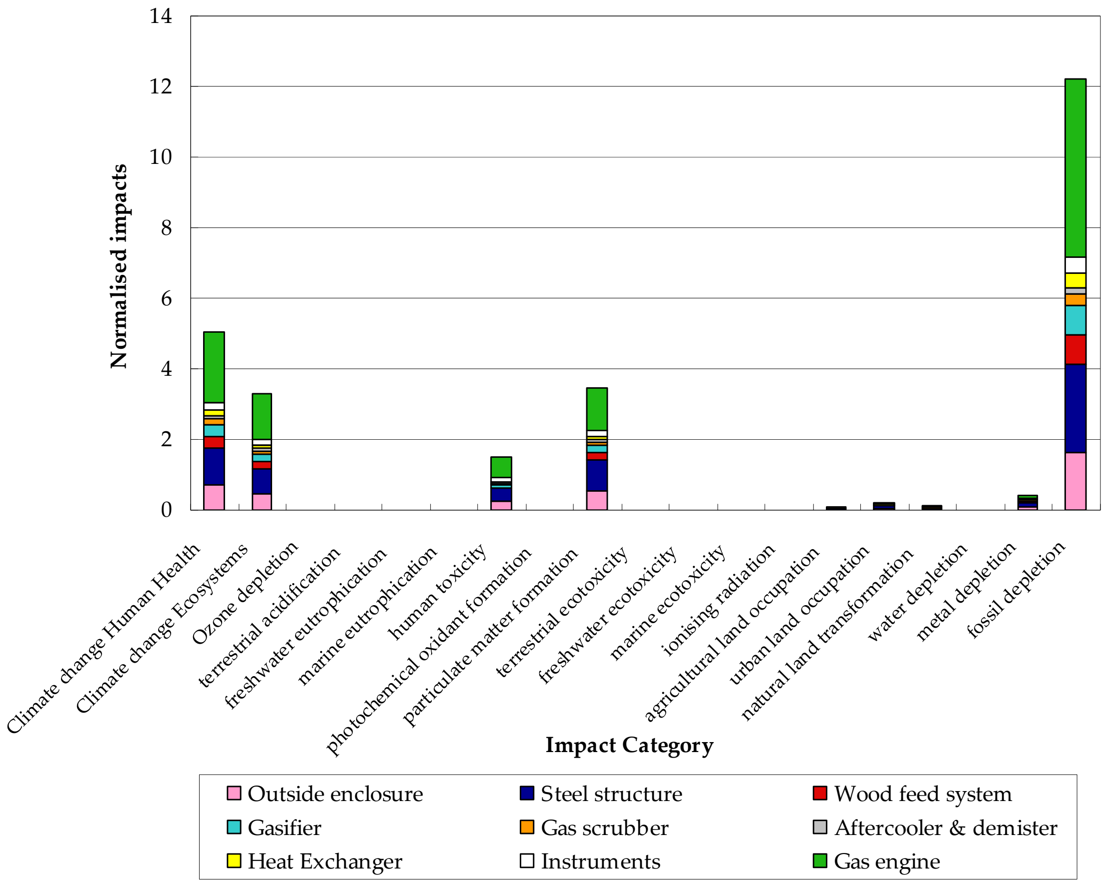


Figure 8-2: Normalised Data for Gasification Plant Construction – ReCiPe endpoint (H/A)

8.3.1.2. Eco-Indicator 99

Eco-indicator 99 produces very similar results to ReCiPe in terms of the contribution to each impact category of the different groups of equipment. Consequently, further analysis focuses on the impact categories, rather than the relative contributions of the different groups of equipment. Normalised results showed that the key issues identified are similar to ReCiPe, although the impact categories identified as important arise in a slightly different order (see Figure 8-3). Mineral depletion is identified in Eco-Indicator 99 as the key issue of concern. Fossil fuel depletion, respiratory inorganics and climate change are again all important, along with ecotoxicity which is similar to the human toxicity category in ReCiPe. By assessing the potential impacts using Eco-Indicator 99 a useful verification of the results from ReCiPe (endpoint) has been provided. It is therefore possible to draw some conclusions on the impact categories which are most relevant to the plant construction. In ReCiPe these key issues can be summarised as:

- Climate change (both damages to Human Health and damages to Ecosystems)
- Particulate matter formation *(equivalent to respiratory inorganics in Eco-Indicator 99)*
- Human toxicity
- Metal depletion
- Fossil fuel depletion

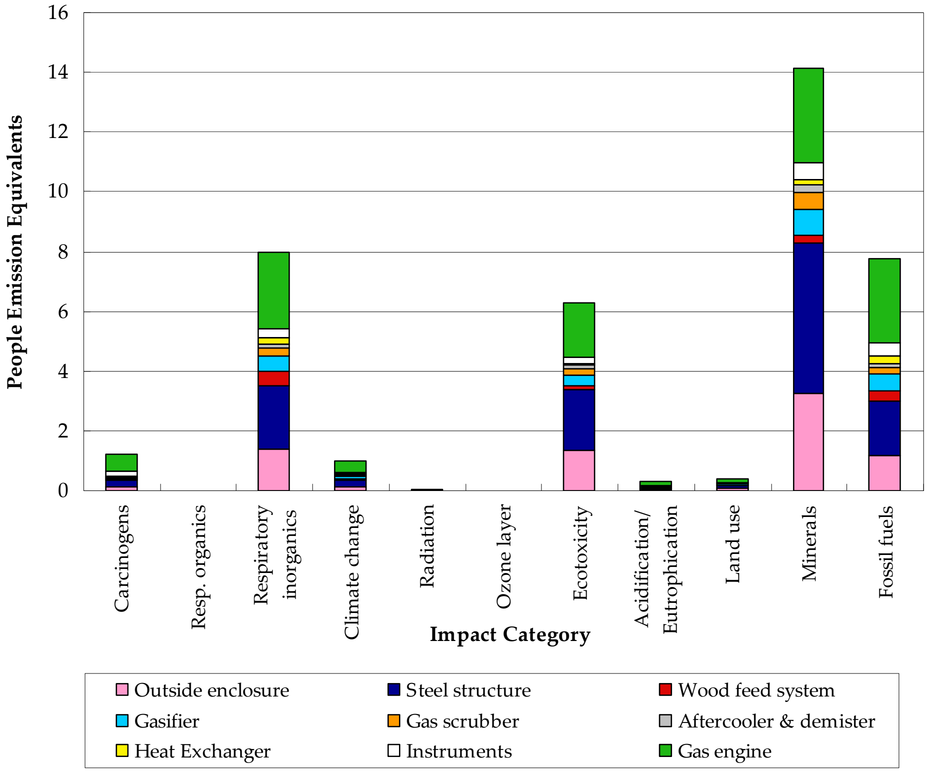


Figure 8-3: Normalised Data for Gasification Plant Construction – Eco-Indicator 99 (H)

8.3.1.3. ReCiPe (midpoint)

Having identified the predominant impact categories from ReCiPe (endpoint), this section provides some further analysis at the midpoint level. As discussed above, the main contribution to the most important impact categories is the high use of metal in the plant with its associated sub-processes. Each of these impact categories is now further assessed using ReCiPe (midpoint), with a particular focus on metal use. The endpoint results for these impact categories are presented alongside the midpoint results in Table 8-3.

Table 8-3: Life cycle impacts for the construction of the Biomass Gasification Plant – ReCiPe (midpoint & endpoint)

Impact category	Midpoint Results		Endpoint Results	
	unit	Total	unit	Total
Climate change Human Health	kg CO_2 eq.	72,921	DALY	0.1020846
Climate change Ecosystems	-		species.yr	0.0005782
human toxicity	kg 1,4-DB eq.	43,485	DALY	0.0304336
particulate matter formation	kg PM_{10} eq.	268	DALY	0.0696618
metal depletion	kg Fe eq.	177,402	$	12,672
fossil depletion	kg oil eq.	34,732	$	373,604

Metals are a finite resource and are easily the most widely consumed elements in the plant, so it is understandable that **metal depletion** comes out as potential issue. A total of 177,402kg Fe eq. is consumed in the construction of the BGP, with the biggest components being the steel structure (58,561kg Fe eq.), gas engine (43,335kg Fe eq.), outside enclosure (37,915kg Fe eq.), and gasifier (11,067kg Fe eq.).

Different grades of steel are the most common materials used in the plant construction. Each type of steel uses a combination of elements which have to be mined, extracted, produced and processed. In particular; iron, chromium, nickel and molybdenum, are all extracted to produce stainless steel. Each of these metals has a different characterisation factor as shown in Table 8-4, which explains why the total kg Fe eq. is greater than the total weight of the plant.

Table 8-4: Midpoint characterisation factors for selected metals in ReCiPe (source: Goedkoop *et al.*, 2009)

Metal	Symbol	Midpoint characterisation factor (Fe eq.)
Chromium	Cr	2.49
Iron	Fe	1
Molybdenum	Mo	20.8
Nickel	Ni	1.25

The average content of recycled materials used in stainless steel produced in the UK is 60% (see Appendix G). This means that approximately 40% of stainless steel is made from virgin metals, which are a limited resource. Therefore this category could be reduced by using a higher recycled steel content. In contrast, the overall impact of plant construction is already much lower than if 100% virgin metals were used in stainless steel. Aluminium, copper and zinc are also extracted for use in equipment in the gasification plant, but their use is much lower than the metals used in stainless steel.

Particulate matter formation is also a significant impact category in the construction of the plant. A total of 268kg PM_{10} eq. were found to be released through plant construction. Chromium production was found to have the highest release of particulates with ~54kg PM_{10} eq. Iron ore mining (~28kg PM_{10} eq.), nickel production (~23kg PM_{10} eq.), and hard coal burnt in steel production (~20kg PM_{10} eq.) were the main causes of particulates.

Damage to human health caused by particulate matter arises primarily from the use of fossil fuels in upstream processes. For example, ferronickel, ferrochromium and molybdenum production all require coal to be burnt in an industrial furnace to reach the required temperatures to extract the metal. Burning coal releases particulates, carbon monoxide, NO_x, SO_x, and VOCs, which can cause respiratory effects in humans. Electricity use in these production processes is also quite high; emissions associated with electricity use are discussed in Appendix G. Ammonia released during production of molybdenum and copper also contributes to particulate matter formation, largely because ammonium nitrate is used in producing the explosives used in blasting undertaken during mining.

Toxicity is an important impact category in metal production, primarily as metal elements are the main emissions which contribute towards this environmental issue. Metals are extracted from a deposit (that is extracted from a mine) and most deposits contain several minerals. This means that metal deposits have to be separated, and hence extractive metallurgy produces slag, a toxic waste, which needs to be disposed of. For example, ferronickel production generates nickel smelter slag which is disposed of at landfill. It contains several elements which leach into water causing pollution.

Further analysis of the main contributions towards **human toxicity** shows that the release of toxic substances is caused by the production of steel, ferronickel, ferrochromium, molybdenum, copper and zinc. The inventory generates a total of 43,485 kg 1,4-DB eq. for human toxicity, of which ~17,108kg are attributable to Mercury released to air. Arsenic (~8,453kg) and lead

(~8,142kg) released to air also account for much of these emissions. Various other metals including cadmium, manganese and zinc are also released to air and water. In addition, transportation contributes towards toxicity through the combustion of fuel, although its contribution is much lower than metal extraction and processing.

All construction materials used in the production of the plant require energy to produce; this energy is almost always provided by fossil fuels. Indeed, even the UK electricity grid is reliant on fossil fuels for more than 80% of production (see Table 7-6). **Fossil fuel depletion** is therefore a key impact category due to the high reliance on non-renewable energy for sub-processes. This is perhaps most clearly demonstrated by looking at the LCI of 1kg of stainless steel (see Appendix G), where coal, crude oil, natural gas, lignite and UK grid electricity are all consumed in production. Indeed, the electric arc furnace used in stainless steel production also has a high energy demand, which is predominantly supplied by fossil fuels. Metal mining, extraction, production and processing is energy intensive, which means there is heavy reliance on fossil fuels which are finite and release several pollutants Transportation of materials, particularly metals can also be significant and contributes to fossil fuel depletion through the use of transport fuels.

A total of 34,732kg oil eq. is consumed in constructing the BGP, which contributes towards fossil fuel depletion. The fossil fuel sources consumed were found to be coal (~15,654kg oil eq.), natural gas (~7,933kg oil eq.), crude oil (~7,728kg oil eq.), lignite (~2,113kg oil eq.), and other sources account for the remaining ~1,304kg oil eq. This can also be analysed by the amount of fossil fuels consumed in producing the individual elements of the BGP. The three items which consume the most fossil fuels are the steel structure (~10,601kg oil eq.), gas engine (~9,593kg oil eq.) and the outside enclosure (~6,866kg oil eq.).

Climate change impacts were found to be closely related to fossil fuel consumption in plant construction. A total of 72,921kg CO_2 eq. were found to be released, with coal burning making the largest contribution towards this (~37,358kg CO_2 eq.).

8.3.2 Plant Operation LCIA

This section shows the LCIA results for the Biomass gasification plant (BGP) operational stage. A base case is used to allow the results to be assessed based on the LCI described in Chapter 7 section 3.2. As stated in the LCI, the base case results assume that the plant has a lifetime of 20 years, operates for 2,500 hours a year and is started up 100 times during the year. Results presented here assume a net electrical output of 828MJ/hr (230kW) and the heat is not utilised and is emitted as waste heat. Hence the functional unit of 1MJ of energy is identical to 1MJ of electricity produced. As a CHP plant increasing the amount of useful heat generated will affect the results by reducing the emissions per unit output. Different allocation methods for dealing with the heat are assessed in 8.3.3, with further analysis performed in Chapter 9.

It is necessary to restate these assumptions as they have different effects on the results, which are further assessed in the sensitivity analysis. Using a base case gives the results based on the best estimate of normal operating conditions. The subsequent sensitivity analysis assesses the effect of different assumptions where the LCI data is less certain.

During operation of the plant, direct environmental releases include ash generated from the gasification process, wastewater effluent from gas scrubbing, and flue gas emissions from producer gas combustion (see Figure 7-5). Indirect emissions arise principally from sub-processes associated with the manufacturing of materials used in the construction of the plant and the use of UK grid electricity. Each of these plant operation aspects are assessed in the following sub-sections.

8.3.2.1. ReCiPe (endpoint)

Characterised results are helpful to illustrate the relative contribution of each aspect of the plant operation to every impact category. Figure 8-4 displays the characterised results for the operation of the BGP, based on the LCI described in section 8.2.2.

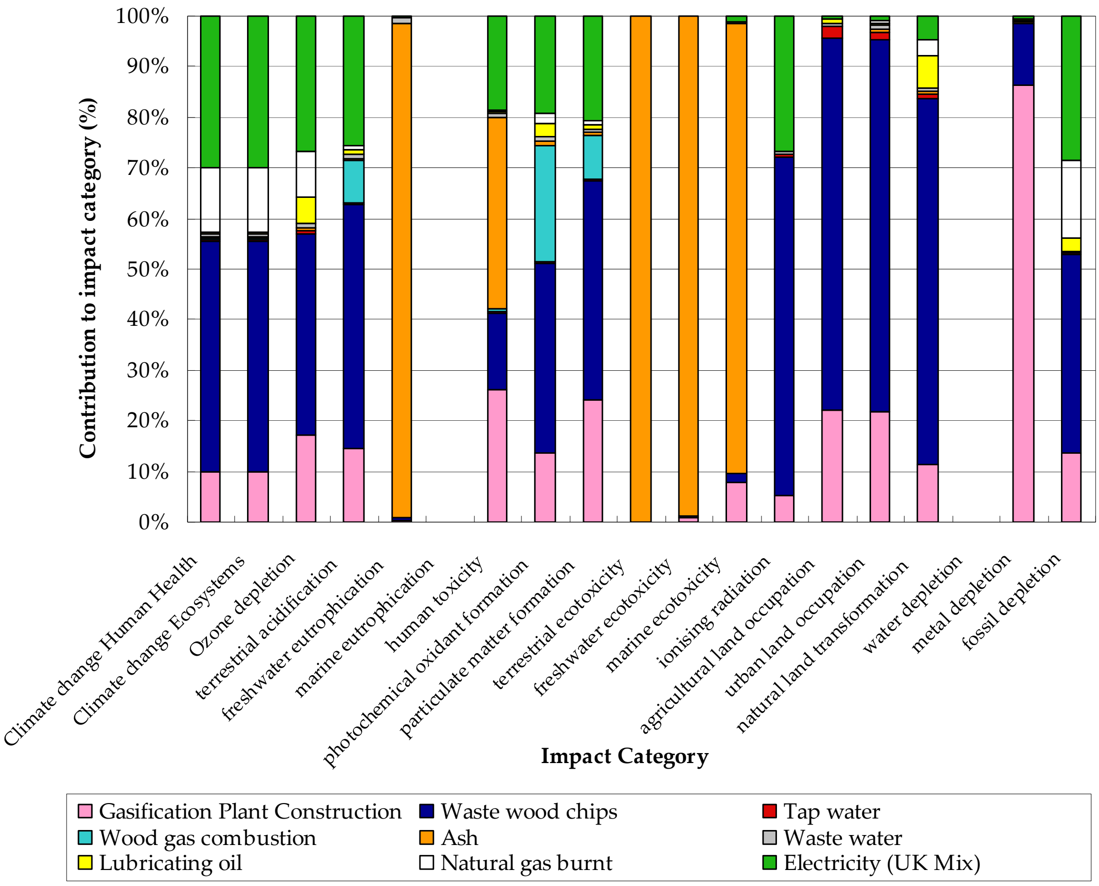


Figure 8-4: Characterised Data for Biomass Gasification Plant Operation (per MJ of electricity produced) – ReCiPe endpoint (H)

The main findings from the characterised data for the plant operation using ReCiPe (endpoint) can be summarised as:

- Plant construction contributes to every impact category, and makes the largest contribution to metal depletion (~86%).
- Waste wood (which includes wood chipping into sawdust) also contributes to every impact category, most notably being land occupation (~74%), fossil fuel depletion (~39%), particulate matter formation (~43%), and climate change (~46%).
- Electricity consumed in the plant follows a similar pattern to waste wood (with the exception of land use) but lower totals.
- Natural gas used on start-up contributes ~15% to the fossil fuel depletion category and ~13% to climate change.

- Wood gas combustion does not contribute towards climate change and accounts for only ~9% of particulate matter formation, which is a surprising result which is assessed in further detail below and in Chapter 10.
- Ash makes up almost all of the contribution to the ecotoxicity categories and ~38% of the human toxicity category.
- Lubricating oil makes a small contribution (~5%) to fossil fuel depletion.
- Water use and water treatment were found to have a minimal impact.

These characterised results are useful for seeing the relative contribution of different aspects of the plant operation. The normalised results are therefore important to show the impact categories in the plant operation with the largest relative impacts (see Figure 8-5).

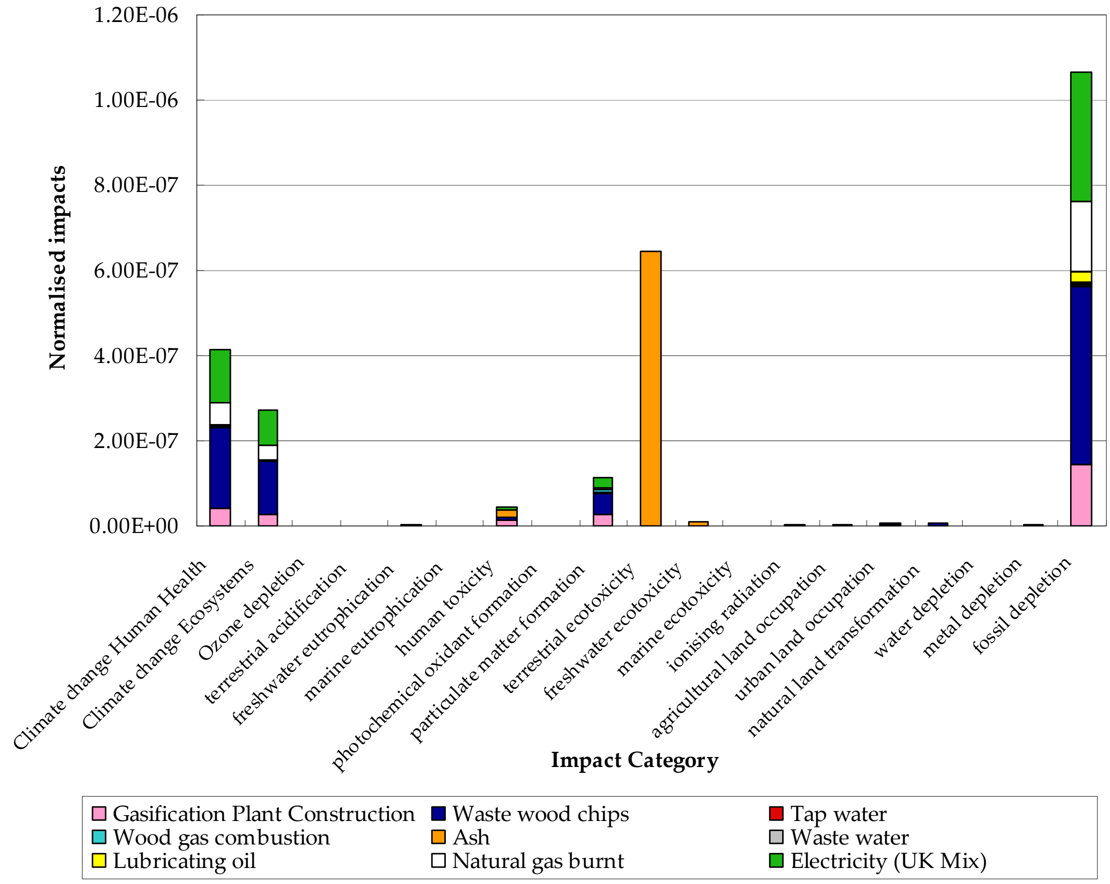


Figure 8-5: Normalised Data for Biomass Gasification Plant Operation (per MJ of electricity produced) – ReCiPe endpoint (H/A)

Normalised results using ReCiPe (endpoint) clearly show that fossil fuel depletion is the most important impact category. Combustion of fossil fuels is known to release several greenhouse gases and inorganic substances. This largely explains why climate change and particulate matter formation were also found to be important impact categories. Human toxicity is a relevant impact category, but metal depletion was not found to be a key issue when the operation of the plant considered.

8.3.2.2. Eco-Indicator 99

Having presented the main results from the plant operation above using ReCiPe (endpoint), results are now assessed using Eco-Indicator 99 to verify the key issues. Characterised results using Eco-Indicator 99 were found to make similar contributions as ReCiPe to most impact categories, with the exception of ecotoxicity and climate change. Ecotoxicity is different in Eco-Indicator 99 as a characterisation factor for phosphorous is not included which significantly reduces the impact of ash when compared to ReCiPe. Climate change is also different as biogenic emissions in wood gas combustion are accounted for in Eco-Indicator 99, whereas ReCiPe does not account for biogenic emissions.

Normalised results for Eco-Indicator 99 (displayed in Figure 8-6) rate the importance of the impact categories in a slightly different way to ReCiPe. However, as with plant construction, the key issues identified are very similar to ReCiPe, albeit in a slightly different order. One notable difference in the normalised results is that mineral depletion comes out as an important impact category in Eco-Indicator 99, whereas in ReCiPe this was less important. By assessing the potential impacts using Eco-Indicator 99 a valuable confirmation of the key issues from ReCiPe (endpoint) has been provided.

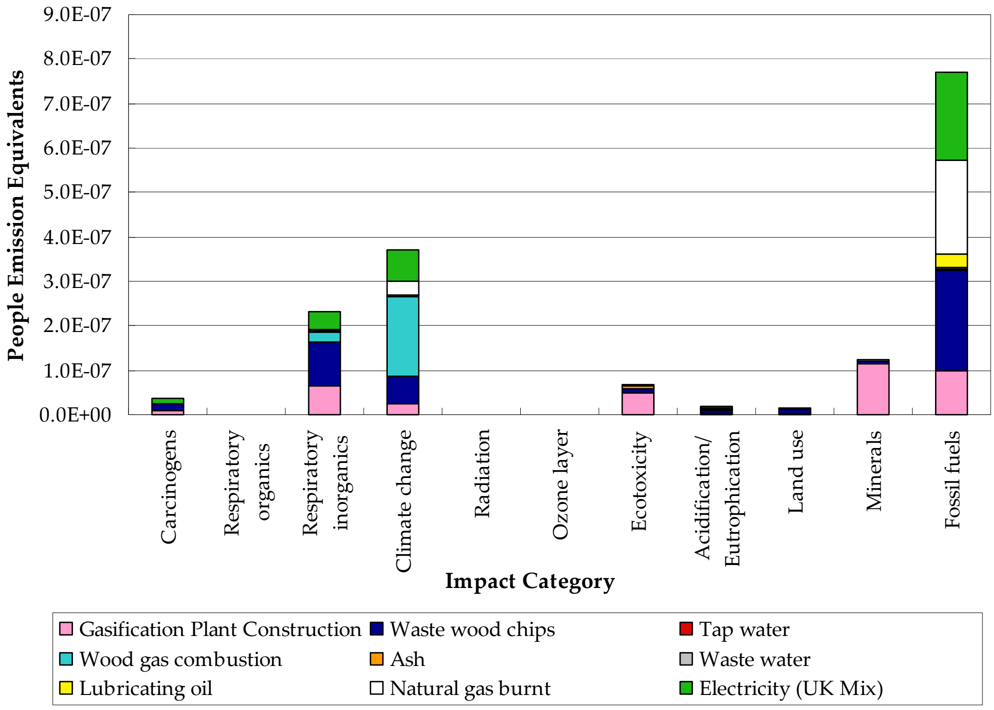


Figure 8-6: Normalised Data for Biomass Gasification Plant Operation (per MJ of electricity produced) – Eco-Indicator 99 (H)

8.3.2.3. ReCiPe (midpoint)

Endpoint results identified six key issues for the gasification plant operation: fossil fuel depletion, climate change, particulate matter formation, human toxicity, terrestrial ecotoxicity and metal depletion. Each of these is now investigated using the midpoint indicators to obtain a better understanding of each impact category. Table 8-5 displays the life cycle impacts for the production of 1MJ of electricity using ReCiPe (midpoint). Heat produced by the gasification process is not assessed here so results are presented assuming waste heat. Instead heat production is assessed in the section on allocation (see section 8.3.3). Owing to the relatively small numbers for life cycle impacts on a 'per **MJ** of electricity basis' (see Table 8-5), subsequent analysis of results uses **GJ**, to make the results more presentable. Figure 8-7 summaries the characterised midpoint results for the plant operation.

Table 8-5: Life cycle impacts for the production of 1 MJ of electricity from biomass gasification – ReCiPe (midpoint & endpoint)

Impact category	Midpoint Results		Endpoint Results	
	unit	Total	unit	Total
climate change human health	kg CO_2 eq.	5.99×10^{-03}	DALY	8.39×10^{-09}
climate change ecosystems	-		species.yr	4.75×10^{-11}
particulate matter formation	kg PM_{10} eq.	8.90×10^{-06}	DALY	2.31×10^{-09}
human toxicity	kg 1,4-DB eq.	1.33×10^{-03}	DALY	9.32×10^{-10}
terrestrial ecotoxicity	kg 1,4-DB eq.	2.66×10^{-03}	species.yr	3.38×10^{-10}
water depletion	m^3	0.0001601	-	
metal depletion	kg Fe eq.	0.0016471	$	0.0001176
fossil depletion	kg oil eq.	0.0020245	$	0.0325639

Fossil fuel depletion is relatively straight forward to break down as the contributions are based on the relative amount of fossil fuel energy consumed from each aspect of the plant operation. In total ~2.02kg of oil eq. is consumed per GJ of electricity produced, which is broken down as electricity consumed in wood processing (~0.79kg), plant operation electricity (~0.54kg), natural gas (~0.30 kg) and plant construction (~0.28kg) and lubricating oil (~0.05kg). Other aspects of the plant operation were found to contribute less than 1%. Fossil fuel depletion is assessed further in the net energy analysis in Chapter 9.

Climate change follows a similar break down as fossil fuel depletion. In total 5.99kg of CO_2eq. are released per GJ of electricity produced, which is broken down as wood waste (~2.73kg), plant operation electricity (~1.80kg), natural gas (~0.76kg) and plant construction (~0.60kg). Other aspects of the plant operation were found to contribute less than 1%. It is important to note that biogenic CO_2 from wood gas combustion is not accounted for in ReCiPe (see work performed in Chapter 10).

Particulate matter formation arises primarily from upstream processes associated with UK grid electricity and plant construction, although the contribution of wood gas combustion is also notable. A total of 8.9g of PM_{10} eq. were found to be released per GJ of electricity produced; the use of electricity contributes about 64% (~5.6g) of these emissions, with ~2.2g coming from plant construction. Emissions from wood gas combustion were found to be ~0.8g per GJ of electricity produced, which is well within various emission limits. Primary data could not been obtained for NO_x and particulates in the LCI, therefore this is assessed further in the sensitivity analysis.

Human toxicity is influenced mainly by the composition of the ash. In the base case a total of ~1,331g 1,4-DB eq. are released to the air per GJ of electricity produced, with the contribution from ash being ~502g. Electricity consumption contributes a further ~450g with plant construction accounting for ~349g. Waste water was found to contribute about 1% (~13g). Therefore the human toxicity category is influenced by both direct plant emissions, i.e. ash and waste water, and indirect emissions, such as electricity and plant construction.

Phosphorous contained in the ash was found to contribute 100% to the **terrestrial ecotoxicity** impact category. The total of 2,665g 1,4-DB eq. is released to freshwater per GJ of electricity produced.

Metal depletion is most affected by the construction of the plant, as described in section 8.3.1. Plant construction accounts for ~1.42kg Fe eq. per GJ of electricity produced (86%), of the total

~1.65kg Fe eq. Most of the remaining contribution comes from the construction of the wood-chipper used to produce the waste wood chips. This was found to consume ~204g Fe eq. per GJ of electricity produced.

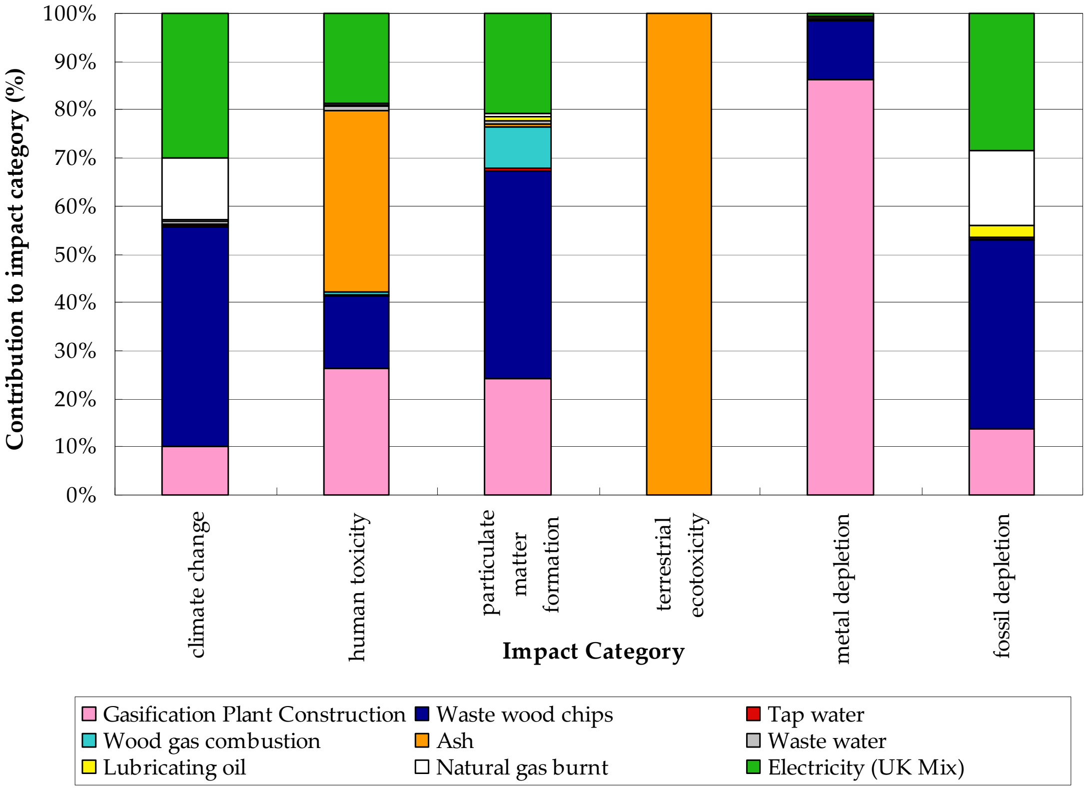


Figure 8-7: Characterised Data for Gasification Plant Operation – ReCiPe midpoint (H)

8.3.3 Allocation

Combined heat and power production offers a rise in fuel efficiency, leading to a decrease of environmental burdens per unit of useful energy. Different options exist for the attribution of environmental impacts to either heat or electricity (Jungmeier *et al.*, 1998):

- Allocation based on operational characteristics (electricity only, heat only, credits for electricity, and credits for heat)
- Allocation based on thermodynamic parameters (energy content, exergy content)
- Allocation based on the final products prices
- Avoiding allocation

These different options for allocating the environmental burdens to heat and electricity produce a wide range of possible results. LCIA findings from the plant operation (presented in section 8.3.2) assumed that the heat was not utilised and emitted as waste heat. This effectively meant that the environmental burdens of the plant were allocated 100% to electricity. However, as a CHP plant, heat is produced and utilised so it is important to highlight the different options for accounting for this. To illustrate this an example from (Jungmeier *et al.*, 1998) is adapted using actual BGP operation data. The annual production is 2,070GJ (575MWh) of electricity, 4,500GJ (1,250MWh) of heat and the annual particulate matter formation (PMF) is 18.43kg PM_{10} eq. This assumes that 100% of the heat is utilised and there are 2,500 annual operating hours. The following sub-sections compare the different allocation methods using this data.

8.3.3.1. Operational characteristics

A CHP Plant is operated to primarily satisfy a predefined demand of either electricity or heat, so that the additional production of heat or electricity respectively may be considered a by-product. To calculate the burdens per unit electricity (or heat), on one hand all emissions are attributed to electricity (or heat) and on the other hand credits for the production of heat (or electricity) is taken into account (Jungmeier *et al.*, 1998). The credits are determined by the environmental burdens avoided due to replacing other technologies, with by-products.

To calculate the credits for heat a natural gas-fired industrial furnace with annual particulate emissions of 75.82kg PM_{10} eq. (60.7g/MWh) from Ecoinvent was used; to calculate the credits for electricity a natural gas-fired power plant with annual particulate emissions of 29.29kg PM_{10} eq. (50.9g/MWh) from Ecoinvent was used (Swiss Centre for Life Cycle Inventories, 2009). The results for allocation using operational characteristics (n.b. g represents number of grams (g) of PM_{10} eq.) are summarised as:

- **Electricity only –** has PM_{10} eq. emissions of 32.1g/MWh and heat has 0g/MWh;
- **Heat only** – has PM_{10} eq. emissions of 14.7g/MWh and electricity has 0g/MWh;
- **Credits for heat** – has PM_{10} eq. emissions for heat of 60.7g/MWh and electricity has minus 99.8g/MWh
- **Credits for electricity** – has PM_{10} eq. emissions for electricity of 50.9g/MWh and heat has minus 8.7g/MWh.

8.3.3.2. Thermodynamic parameters

In this method the energy and exergy content of the products electricity and heat are used as a weighting factor for the allocation of environmental burdens between electricity and heat. **Energy** allocation is based on the energy content of the annual electricity and heat production (Jungmeier *et al.*, 1998). The total energy production is 1,825MWh (32% electricity and 68% heat) that means both electricity and heat have the same PM_{10} eq. emissions of 10.1g/MWh.

Exergy allocation is based on the exergy content of the annual electricity and heat production. The exergy content of electricity and heat is characterised by the Carnot-factors (η_C) with $\eta_C = 1$ for electricity and $\eta_C = 0.2$ for heat (Jungmeier *et al.*, 1998). The annual exergy production is 825MWh (70% electricity and 30% heat). With this allocation electricity has PM_{10} eq. emissions of 22.3g/MWh and heat of 4.5g/MWh.

8.3.3.3. Product prices

The **final product prices** of electricity and heat are used as a weighting factor for the allocation of the environmental burdens between electricity and heat. The prices on the demand side for medium-sized industrial users were used to calculate the annual income. The average price for industrial consumers was obtained from DECC as 6.219p/kWh for electricity and 1.603p/kWh for natural gas (DECC, 2010c). This gave a total annual income of £55,797 (64% from electricity and 36% from heat). With this allocation electricity has PM_{10} eq. emissions of 20.5g/MWh and heat of 5.3g/MWh.

8.3.3.4. Avoiding allocation

Avoiding of allocation means, that electricity and heat are not treated separately, and the functional unit is therefore a "package" of 0.32kWh electricity plus 0.68kWh heat, which reflects the ratio from electricity to heat with 1:2.17. This functional unit avoids allocation and leads to PM_{10} eq. emissions of 10.1g/(0.32MWh electricity and 0.68MWh heat).

8.3.3.5. Summary

Table 8-6 and Figure 8-8 show the results of the different allocation of environmental burdens to combined heat and electricity production, using the example of PM_{10} eq. emissions. Each of these allocation options could be applied to the LCIA results presented in sections 8.3.1 and 8.3.2. This has not been included in this thesis as these allocation methods are presented for discussion purposes. However, with the example provided for particulate matter formation (PM_{10} eq.) different allocation options are straightforward to apply to other impact categories. The use of a given allocation method depends on the goal and scope of the study. In this case study the primary purpose of the CHP unit is to satisfy the demand for electricity, so the LCIA results are allocated to electricity only.

Table 8-6: Comparison of different allocation options of PM_{10} eq. emissions for electricity and heat (based on the methodology presented by Jungmeier *et al.*, 1998)

		Electricity	Heat
		g/MWh	
Operational characteristics	Electricity only	32.1	0
	Heat only	0	14.7
	Credit heat	-99.8	60.7
	Credit electricity	50.9	-8.7
Thermodynamic parameters	Energy	10.1	10.1
	Exergy	22.3	4.5
Products price	Price	20.5	5.3
Avoid allocation		g/(0.32MWh_e + 0.68MWh_{th})	
		10.1	

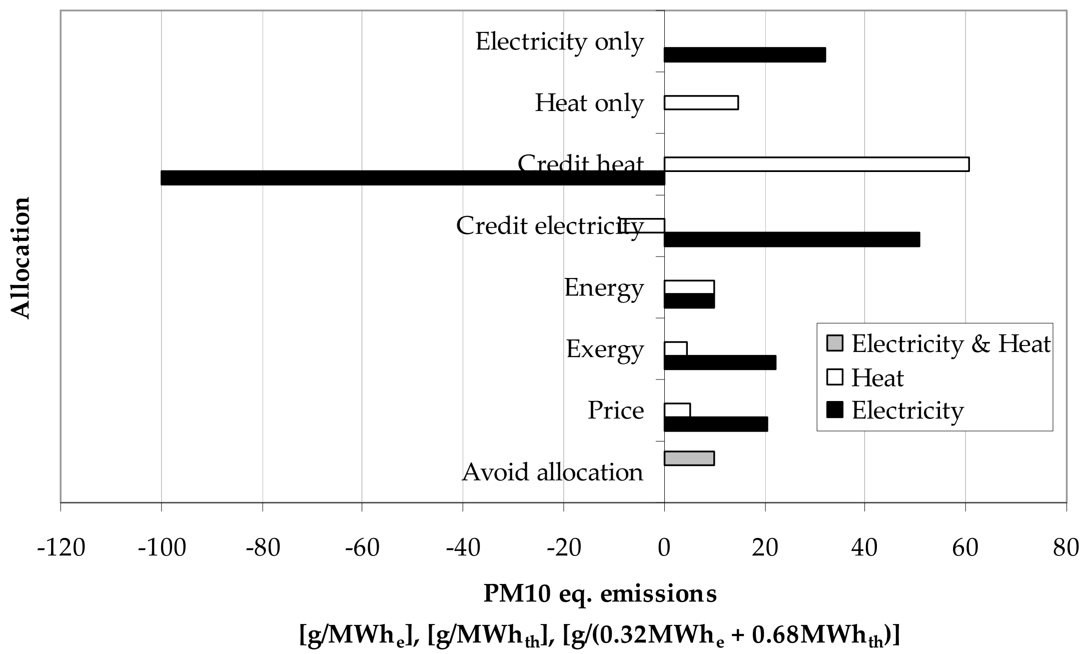


Figure 8-8: PM_{10} eq. emissions for different allocation options for electricity and heat

8.3.4 Heat demand

Electricity produced in the CHP plant is either utilised on site or, if there is an excess, fed back into the UK grid. The situation with using the thermal output depends on the end-user demand for heat. For example, heat demand will be higher in the colder, winter months and therefore heat produced in this period is likely to be fully consumed. Conversely in the warmer summer period the heat demand will be lower and so much of the heat produced will be wasted. This concept is referred to as degree days (Carbon Trust, 2010). The effect of modelling heat demand depends on the allocation method chosen (see section 8.3.3) and the actual delivered heat output. Clearly the emissions from the plant operation will be the same per hour of operation, but how these are allocated between electricity and heat production can vary considerably. Results presented in section 8.3.2 allocate the life cycle impacts to electricity only; these would therefore change according to the allocation method chosen and indeed the heat utilisation. The effect of heat demand on net energy analysis results is assessed in Chapter 9.

8.4 LIFE CYCLE INTERPRETATION

This section highlights and discusses the significant issues of each aspect of the plant operation, based on the work performed in sections 8.2 (LCI) and 8.3 (LCIA). A sensitivity analysis is then performed to show how results can vary when the assumptions are altered. Finally some conclusions and recommendations are presented.

8.4.1 Significant issues based on the LCI and LCIA

Key issues found from the impact assessment of plant construction and operation were presented in sections 8.3.1 and 8.3.2; hence this section provides more detail on each aspect of the plant operation; a discussion of the issues based on the LCI and LCIA is provided.

8.4.1.1. Plant construction

Impacts from the construction of the plant were scaled down to give the amount of plant required to produce 1MJ of electricity (see section 7.3.2.1). Overall the operation of the plant has a more significant potential impact on the environment than its construction, except in the metal depletion impact category, based on a lifetime of 20 years and operating for 2,500 hours a year. However, it is useful to note that the construction of the plant contributes towards each impact category. Different plant lifetimes and operating hours do have an affect on the relative contribution of the plant construction. For example, a longer lifetime or more operating hours will reduce the relative impact of construction. These are consequently analysed in the sensitivity analysis. The impacts of plant construction have been assessed in section 8.3.1, so are not further discussed here.

8.4.1.2. Waste wood chips

Processing the feedstock through wood chipping is a relatively energy intensive operation. For every m^3 of wood which is chipped, 27MJ (7.5kWh) of delivered UK grid electricity is consumed. This impact of using grid electricity makes a contribution to each of the impact categories due to the diverse range of electricity supply (see section 7.3.2.11). In addition, the wood chipper uses 2 motors and two tonnes of steel which contributes towards metal depletion. Land use is also quite high due to the area needed to store the wood chip, and the upstream processes associated with electricity production.

8.4.1.3. Natural gas burnt

Natural gas consumed in the pre-burner contributes to both fossil fuel depletion and a climate change. Natural gas use also impacts on particulate matter formation through the release of nitrogen oxides, sulphur dioxide and particulates. The number of start-ups and the length of each start-up are the foremost determinants of the impact of using natural gas, and are assessed further in the sensitivity analysis. LCI data was considered to be good quality as emissions from burning natural gas are well known.

8.4.1.4. Ash disposal

Ash is the inorganic residue that remains after combustion of the biomass in the gasification process (Higman & van der Burgt, 2008). Composition of the ash depends on several factors including primarily the feedstock composition, but also the type of gasification system, temperature and pressure. The main elements found in the ash are chemical elements such as sulphur, calcium, phosphate and potassium and various metals. These are found in quite small quantities and therefore do not often have a notable impact.

Potential impacts of ash disposal include ecotoxicity, human toxicity and freshwater eutrophication. This is due to the emissions to soil and water of metals such as chromium, copper, iron, lead and zinc. Further analysis reveals that phosphorous contained in the ash is the main determinant of the potential impact from ash disposal. Transportation of the ash does not have a notable impact as only one journey is required per year.

Primary LCI data on the ash composition could not be obtained for this study. However, the amount and composition of ash will affect the characterised results, hence ash disposal is further assessed in the sensitivity analysis.

8.4.1.5. Waste water and water use

Waste water is emitted from the BGP in the form of condensate from gas cleaning and scrubbing. Condensate from non-contaminated wood consists mainly of water and low amounts of tar. The condensate is purified enough to be put directly into the sewer system. Although the characterised data used for waste water show no notable impacts, the composition of the waste water effluent will affect the results. Primary LCI data on waste water composition could not be obtained for this study. Therefore, the impacts associated with different characterised data and compositions are assessed in the sensitivity analysis.

The impact category water depletion in ReCiPe (endpoint) does not model any endpoint lifetime impacts. This may appear conflicting with the midpoint results, which displays releases for water use. However, the midpoint records the physically quantifiable release of water. Hence water depletion may be a potential issue to consider (see Chapter 10).

8.4.1.6. Producer gas combustion

As with any fuel, the combustion of producer gas (or wood gas) can generate gaseous pollutants. The major contaminants found in the exhaust gas are nitrogen oxides (NO_x), carbon monoxide (CO), sulphur dioxide (SO_2), volatile organic compounds (VOCs), particulate matter (dust, unburnt carbon), and trace species such as metals (Lieuwen *et al.*, 2010). During combustion, several chemical reactions occur and develop different reaction products depending on the pressure, temperature, and oxygen and nitrogen concentration (Deublein & Steinhauser, 2008).

The concentrations of these main compounds vary depending on the properties of the producer gas, the engine type and operating conditions of the gas engine. A brief description of each of these pollutants is given together with the impact on the case study results.

- CO_2 (and CH_4) released from combustion of wood gas are considered to be biogenic. ReCiPe does not account for these emissions; hence the impact on climate change is zero. Modelling of biogenic emissions is further assessed in Chapter 10.
- Deublein and Steinhauser (2008) show that the NO_x content of the exhaust increases with the methane content of biogas, whilst other impurities like CO, formaldehyde, and unburnt carbon decrease with increasing methane content. This helps to explain why NO_x emissions are assumed to be relatively low, i.e. due to the low methane content of the producer gas.
- NO_x and particulates contribute to particulate matter formation (PMF). Results displayed in section 8.3.2 revealed lower than expected contributions to PMF, which may indicate the LCI data was inaccurate. The modelling used assumed a methodology applied by (Jungbluth *et al.*, 2007), however without actual primary data it is not possible to conclude. The effect of modelling based on emission limits is therefore assessed in the sensitivity analysis.
- Carbon monoxide (CO) in producer gas combustion has two primary sources: unburned syngas CO and incomplete combustion of hydrocarbon species in the syngas (Lieuwen *et al.*, 2010). For the base case it is assumed that emissions of CO are relatively low as all CO contained in the producer gas is emitted as CO_2. When the CO content in emissions is higher, purification systems will be added to satisfy emission limits, and the engine fumes must also be filtered with an oxidation catalyst (Deublein & Steinhauser, 2008).
- Sulphur content in biomass is generally very low (< 0.1% by weight), therefore emissions such as sulphur dioxide (SO_2) are minimal in biomass gasification systems (ECN, 2009; Higman & van der Burgt, 2008). In comparison coal and natural gas contain a higher percentage of sulphur, which means nearly all sulphur compounds must be removed prior to combustion in a gas turbine or engine (Lieuwen *et al.*, 2010). Where sulphur is present in the feedstock and hence producer gas, combustion can lead to the release of SO_2 which can cause an impact on PMF and acidification.
- Volatile Organic Compounds (VOCs) and trace elements found in the producer gas have the potential to impact on human health, particularly causing respiratory problems. These emissions are very minimal with biomass gasification, and are therefore not further considered in this thesis.

8.4.1.7. Electricity used in the plant

Although the amount of electricity used in the plant is higher than the electricity used for wood chipping, only 10% comes from the UK grid. This is because UK grid electricity is only consumed when the plant is started up and once it is shut down. Under normal operating conditions, the parasitic load of the plant is supplied by the electricity generated by the gas engine. This means that although more electricity is consumed than in wood chipping, the source of the electricity is different. Consequently the relative impact of using UK grid electricity in the plant is lower than the electricity utilised for wood chipping.

Emissions from using UK grid electricity are both numerous and diverse. It is beyond the scope of this thesis to describe them in detail, but a summary is presented in Appendix G. Fossil fuel depletion is the most significant impact category for electricity use in this study. Using UK grid electricity contributes to all impact categories.

8.4.1.8. Lubricating oil

Fossil fuel depletion is the main impact category which using lubricating oil contributes to. Disposal of lubricating oil has not been included in this study due to insufficient data being available. However, if disposal was included it is likely to have a potential impact on carcinogenic substances and toxicity.

8.4.2 Sensitivity Analysis

A sensitivity analysis was conducted to identify the parameters which had the largest effects on the results of the study. For both the plant construction and operation, various parameters were changed independently so the magnitude of its effect on the base case could be assessed. Changing one variable at a time is useful to analyse the relative effects on the LCIA results. Most of the sensitivity cases assessed are shown in Table 8-7.

Table 8-7: Sensitivity cases for the biomass gasification plant operation

Case letter	Sensitivity case	Base case	Sensitivity	Change from base case
A	Plant construction – recycled metals ecycled	~ 60% recycled metals	90% recycled metals	+50%
B	Plant construction – virgin metals	~ 60% recycled metals	0% recycled (100% virgin)	-100%
C	Plant lifetime – 30 yr.	20 years	30 years	+50% (+ 10 years)
D	Plant lifetime – 10 yr.	20 years	10 years	-100% (- 10 years)
E	Operating hours - low	2,500 hours	1,000 hours	-60% (-2,500 hrs.)
F	Operating hours - high	2,500 hours	7,000 hours	+280% (+4,500 hrs.)
G	*Feedstock composition*	*Waste wood*	*Various*	*Various*
H	Feedstock pre-processing method	Electric wood-chipper	Diesel wood-chipper	Different method (diesel)
I	Collection and transport of feedstock	No collection and transportation	20km round-trip is included	Different method (transportation)
J	Natural gas (no. of start-ups) – low	100 start-ups	50 start-ups	-50% (-50 start-ups)
K	Natural gas (no. of start-ups) – high	100 start-ups	300 start-ups	+100% (+200 start-ups)
L	Ash volume – low	1.98g/MJ	0.99g/MJ	-50% (-0.99g)
M	Ash volume – high	1.98g/MJ	3.96g/MJ	+100% (+1.98g)
N	*Ash composition*	*Wood (average)*	*Various*	*Various*
O	Ash composition	Wood (average)	Inert material	-100%
P	Water (energy) input	0.390 kWh / m^3	0.585 kWh / m^3	+50% (+0.195 kWh)
Q	Waste water treatment	1.193 kWh / m^3	0.984 kWh / m^3	-18% (-0.209 kWh)
R	*Waste water composition*	*Wood (average)*	*Various*	*Various*
S	*Scrubbing fluids used*	*None*	*Various*	*Different method*
T	*Emissions & legislation from syngas combustion*	*Wood (average)*	*Various*	*Various*

Each sensitivity case was assessed using ReCiPe (midpoint) to quantify the effect on emissions and resource consumption relative to the base case for plant operation. All impact categories were included in the sensitivity analysis. In most cases this produced a new set of

LCIA results. However in some cases several variables were assessed or there were insufficient data and so a qualitative assessment was more appropriate *(denoted in italics)*. Sensitivity data were not always possible to obtain due to a lack of data available. Where data was inconclusive a discussion of potential effects on results is provided. A summary of the key findings from the sensitivity analysis is presented below, this includes the main impact categories effected (see Table 8-8). Further supporting information is included in Appendix H.

Table 8-8: Key findings from sensitivity analysis of biomass gasification plant operation (on per MJ of energy produced basis)

Case letter	Sensitivity case	Change from base case	Main impact categories effected (% change)
A	Plant construction – recycled metals	+50%	MD (-35%)
B	Plant construction – virgin metals	-100%	MD (+71%)
C	Plant lifetime – 30 yr.	+50% (+ 10 years)	MD (-29%)
D	Plant lifetime – 10 yr.	-100% (- 10 years)	MD (+86%)
E	Operating hours - low	-60% (-2,500 hrs.)	MD (+129%)
F	Operating hours – high	+280% (+4,500 hrs.)	MD (-55%)
G	*Feedstock composition*	*Various*	*Qualitative assessment*
H	Feedstock pre-processing method (diesel power)	Different method (diesel)	CC (-14%); PMF (+40%); MD (+27%); FD (-5%)
I	Collection and transport of feedstock	Different method (transportation)	CC (+22%); PMF (+19%); FD (+23%)
J	Natural gas (no. of start-ups) – low	-50% (-50 start-ups)	CC (-6%); FD (-8%); NLT (-11%)
K	Natural gas (no. of start-ups) – high	+100% (+200 start-ups)	CC (+25%); FD (+31%); NLT (+45%)
L	Ash volume – low	-50% (-0.99g)	FE; HT; TET; FET; MET (see Appendix H)
M	Ash volume – high	+100% (+1.98g)	
N	*Ash composition*	*Various*	*Qualitative assessment*
O	Ash composition	-100% (inert)	FE; HT; TET; FET; MET (see Appendix H)
P	Water (energy) input	+50% (+0.195 kWh)	<0.4% change in all categories
Q	Waste water treatment	-18% (-0.209 kWh)	<1.1% change in all categories
R	*Waste water composition*	*Various*	*Qualitative assessment*
S	*Scrubbing fluids used*	*Different method*	*Qualitative assessment*
T	Emissions & legislation from producer gas combustion	Various	TA; ME; HT; POF; PMF

Key: MD = Metal Depletion; CC = Climate Change; PMF = Particulate Matter Formation; FD = Fossil Depletion; NLT = Natural Land Transformation; FE = Freshwater Eutrophication; HT = Human Toxicity; TET = Terrestrial Ecotoxicity; FET = Freshwater Ecotoxicity; MET = Marine Ecotoxicity; TA = Terrestrial Acidification; ME = Marine Eutrophication; POF = Photochemical Ozone Formation

Due to the number of sensitivity cases, the complete LCIA results for each case are included in Appendix H. Key findings from the sensitivity analysis include the following:

- Increasing the use of recycled metals in the BGP reduces all impact categories, most notably metal depletion by 35% (case A). In contrast using virgin metals increases every impact category, including metal depletion by 71% (case B).
- An increase in the plant lifetime (case C) or the number of operating hours (case F) will reduce the relative impact 'per MJ of energy produced' basis for all impact categories, although the total impact of plant operation will increase. The opposite is true for a shorter plant lifetime (case D) or lower operating hours (case E).
- Feedstock composition (case G) can affect several releases from the plant including ash, scrub water effluent and producer gas combustion emissions. Contaminants such as metals can reduce the gasification conversion efficiency increasing the volume of ash and increasing gas cleaning requirements. High nitrogen content will increase the amount of NO_x and PM_{10} eq. produced and reduce the NCV of the producer gas. Insufficient data were available to accurately model this sensitivity case; hence this constitutes an area for further research.
- Using a diesel powered wood-chipper was found to improve the efficiency of wood pre-processing (case H). Less energy is consumed than electricity reducing both fossil fuel depletion (5%) and climate change (14%). However particulate matter was found to increase (40%) as does metal depletion (27%).
- Transportation of feedstock 10km using a 12t lorry to the BGP (case I) increases all impact categories, most importantly is fossil fuel depletion (23%), climate change (22%) and particulate matter formation (19%). Despite these increases biomass gasification has lower impacts for these categories than the UK electricity grid average (see Chapter 10).
- The number of start-ups directly affects the amount of natural gas consumed. Therefore less start-ups (case J) reduces both fossil fuel consumption and climate change, with the opposite being true for more start-ups (case K).
- Ash volume and composition was found to only impact upon eutrophication, human toxicity and ecotoxicty (cases L to O). Phosphorous contained in the ash has the biggest affect on the potential impacts followed by various metals. If the ash is found to be inert then the impact from ash is close to zero.
- Water use and waste water treatment (cases P and Q) were found to have almost no impact on the plant operation.
- Data available for the composition of the waste water (case R) and the effect of using different scrubbing fluids (case S) were insufficient to conclude on the potential impacts of gas cleaning. Clearly more contaminants in the producer gas will cause less desirable products in the waste water and will require different scrubbing fluids to be used. The impacts of this should be further researched.
- When UK emission limit values were assumed from producer gas combustion (case T), particulate matter formation was found to increase by more than 5-fold.

8.4.3 Improvement potential and recommendations

In undertaking this LCA study of a biomass gasification plant (BGP) some areas have been identified which may improve it's environmental burden. To reduce the environmental impact of the plant construction it is recommended that more recycled materials could be used. There may also be scope to use alternative materials with less of an impact. The gas engine, outside enclosure and steel structure provide the biggest potentials for improvement. No data for the plant being decommissioned have been included in the main study as this is a very new technology, which means it is uncertain what will happen to the plant at the end of its life.

However as the plant contains a high proportion of metals, recycling these when the plant is disposed of would generate an environmental benefit. This would negate some of the impacts associated with construction, particularly regarding metal depletion.

Utilising the BGP for a longer lifetime and/or increased operating hours is recommended in order to reduce the relative impact of plant construction, and maximise the benefit of utilising this renewable energy source. Whist this will increase the total impact of plant operation, it will also increase the benefits derived from using biomass as opposed to fossil fuel powered thermal plants. In chapters 9 and 10 it is shown that the BGP has overall advantages over fossil-based thermal power and CHP plants, particularly in regard to fossil fuel depletion and climate change.

To minimise the potential harmful releases from plant operation, it is recommended that contaminants in the feedstock should be avoided. Using clean and consistent feedstock is important to ensure the smooth and continuous operation of the BGP (Knoef, 2005). Where contaminants do arise either in the feedstock or through gases formed in the gasification process, it is recommended that sufficient gas cleaning is applied to prevent erosion, corrosion and environmental problems in downstream equipment. Various options exist for gas cleaning (see for example, Bridgwater, 1995; IEE, 2007; Knoef, 2005)

If reducing fossil fuel use and thus greenhouse gas emissions is a main goal then alternative energy sources should be used for feedstock pre-processing. Diesel was found to be more efficient in terms of primary energy consumed than UK grid electricity. However this also increased the amount of particulates released. Other renewable energy sources such as wind or solar power ought to be considered if an electric chipper is to be used, although there maybe questions over whether sufficient power could be achieved using these sources. The parasitic load of the plant is more likely to be able to use wind or solar power as the electricity demand for the pumps, motors and control equipment requires less power, although there are issues with the intermittency of these energy sources. In any case, consideration should be given to the primary energy requirements of pre-processing as this is an energy intensive stage of production.

Transportation of feedstock should be avoided if possible, particularly where long distances are involved. Using waste on site is an ideal situation which makes this possible. However in many cases, particularly if energy crops are used, transportation is essential and therefore travel distances should be minimised. Conversely, in Chapter 10 it is demonstrated that when the entire life cycle is assessed transportation does not make a big overall contribution, based on short distances. Therefore to improve systems where energy crops are required or waste is produced off-site it is recommended that the BGP is located as close to the feedstock source as possible.

Minimising the amount of times the plant is started up will reduce the impact of using natural gas. Therefore longer running periods are recommended to reduce the relative impact on fossil fuel depletion and climate change. Using natural gas does question the sustainability of biomass gasification, therefore alternative fuel sources could be sought to initiate the gasification reactions.

Emissions arising from ash disposal and waste water were not directly obtained from the BGP. It is therefore difficult to conclude on possible ways to improve potential impacts arising from theses releases. Both of these operational emissions are affected by the composition of the feedstock and the gasification process. To ensure optimum performance of the BGP, it is thus crucial that a consistent feedstock is obtained and the operating parameters tailored to maximise the gasification conversion efficiency. Producer gas emissions can also be minimised in a similar manner along with sufficient gas cleaning, as described above. More detailed information and methods of mitigating emissions is available (see for example, EPA, 2008; IEE, 2009b; Knecht, 2008; Oland, 2004).

8.5 SUMMARY

A LCA of a biomass gasification plant (BGP) has been completed in this chapter. Data was obtained in Chapter 7 which produced a unique and novel LCI. This inventory data has subsequently been assessed using the life cycle impact assessment (LCIA) methodology ReCiPe. Findings from this LCIA show that the construction and operation of the BGP has a potential impact on fossil fuel and metal resource depletion, and potential impacts on human health through the release of greenhouse gases, particulates and various other emissions. Many of these potential impacts arise from upstream (or indirect) processes. For example, much of the fossil fuel use in the plant is consumed from UK grid electricity for wood pre-processing and the parasitic load of the BGP. This demonstrates a key benefit of LCA in its accounting of whole 'life cycle' emissions.

Aspects of the plant operation which were found to contribute most to the environmental load of the plant varied for different impact categories. Broadly speaking for fossil fuel depletion, climate change and particulate matter formation it is the wood pre-processing, parasitic electricity demand, and natural gas used on start-up which contributes most to these impact categories. One possible caveat to this is the assumptions regarding the modelling of NO_x and particulates from producer gas combustion. In the sensitivity analysis it was demonstrated that if UK limits are taken as the emissions, then wood gas combustion contributes almost 90% to particulate matter formation. For ecotoxicity and human toxicity most of the contribution arises from the disposal of ash whilst plant construction accounts for the majority of metal depletion.

Overall when the endpoint damage categories are considered over the whole lifetime of the plant the total emissions are low. It can thus be concluded that the BGP construction and operation is considered to have a low environmental impact. To increase the benefits associated with this technology both the electricity and the useful heat consumption should be maximised. This is demonstrated by the allocation methods where by the relative impact of the plant operation is lowest when allocated to electricity and heat.

There are some inconclusive findings from this study which have arisen due to some gaps in the primary data obtained. In particular it was not possible to obtain data on the composition of ash, water or producer gas emissions directly from the BGP. Reliance was therefore placed on the data available in the literature, which has lead to some uncertainties in the results. It is a problem which can be encountered due to lack of sufficient monitoring and recording of emissions, or the commercial confidentiality of companies. This highlights one of the difficulties in undertaking a LCA and also demonstrates the importance of undertaking such studies. As this is an original piece of research a vital finding is that there is a lack of published data available on such emissions. This LCA study therefore provides some useful data and findings which can be used to identify areas for future work, as outlined in Chapter 12.

Findings displayed in this chapter can stand alone as the results analyse and discuss the potential environmental impacts from the BGP chosen for the case study. In Chapter 9 a net energy analysis is undertaken where the energetic benefits of biomass gasification become apparent. Then in Chapter 10 the full life cycle (including crop growth and transportation) is compared to other studies to give a beneficial summary of how this technology compares to different energy systems.

CHAPTER 9. NET ENERGY ANALYSIS OF BIOMASS GASIFICATION

This chapter describes the work performed on the net energy analysis of perennial energy crops and the biomass gasification system. This builds on the life cycle assessment (LCA) studies performed in the previous chapters (6 to 8). Essentially net energy analysis is part of an LCA study as the data collected and system boundary is sufficient to calculate net energy analysis metrics. Results for Miscanthus and SRC Willow are presented first, followed by the biomass gasification system. Some further scenarios are then calculated which include primary energy inputs such as biomass cultivation and transportation. Results are compared to other net energy analysis studies to put the findings in context.

9.1 BACKGROUND

Net energy analysis is a form of chain analysis in which structural pathways in the economic system are delineated and connected to environmental problems (Udo de Haes & Heijungs, 2007). As such, it can be seen as a component of, or a complement to, LCA. Both net energy analysis and LCA aim to analyse the environmental problems associated with products and services throughout their full life-cycle. Clearly, a substantial part of these environmental problems relate in one way or another to energy and related thermodynamic concepts (Udo de Haes & Heijungs, 2007):

- Energy is involved in all life cycles, for example when comparing bioenergy systems energy is used in biomass production, transportation, and conversion;
- It is possible to perform a separate analysis of the energetic aspects of a life cycle;
- LCA can be applied to analyse energy systems, as demonstrated in Chapters 6-8.

One of the primary drivers for expanding the production and use of bioenergy in the UK and worldwide is the potential environmental benefit that may be obtained from replacing fossil-based fuels with fuels derived from more renewable biomass resources. From an energy perspective, however, not all biomass is created equal, nor are all bioenergy production processes equally efficient. It is therefore important to know which bioenergy pathways require more or less energy to produce.

Whilst biomass in itself consists solely of energy photosynthesised with sunlight, producing it requires human effort and outside energy resources (Worldwatch Institute, 2007). Farmers catch the 'free' energy of the sun by seeding, watering and fertilising plants. The biomass that grows must be harvested, transported and converted into a useable fuel. All of these activities use energy; but there is a choice between more and less efficient bioenergy pathways. Some feedstocks are more efficient and easier to produce than others, and some farming and processing methods are more energy intensive than others.

This chapter examines the relative energy requirements of the growth of perennial energy crops (Miscanthus and SRC Willow); the biomass gasification system; and different bioenergy system scenarios. To put the net energy analysis metrics in context a comparison is subsequently made with various studies undertaken on different bioenergy conversion pathways and other energy systems.

9.2 PERENNIAL ENERGY CROPS

When calculating the net energy analysis of a biomass feedstock, the convention of 'cradle to farm-gate' has been applied. This takes the same system boundary for both Miscanthus and SRC Willow (as described in Chapter 6) and calculates the net energy analytics. Hence all of the energy inputs to produce one hectare, or one kilogram of feedstock are included. The delivered energy is taken as the primary energy content of the biomass feedstock.

9.2.1 Miscanthus

Primary energy inputs for the production of one hectare of Miscanthus over an 18 year lifetime were calculated using the life cycle impact assessment method (LCIAM) cumulative energy demand (CED). This LCIAM expresses results in terms MJ, valued as primary energy consumed during the complete life cycle of Miscanthus cultivation. A gross energy requirement (GER) of 120.9GJ for the total primary energy inputs was calculated. The breakdown by each energy source is shown in Table 9-1 and by material in Figure 9-1.

Table 9-1: GER by energy source for one hectare of Miscanthus over 18 year lifetime

Primary energy source	Unit	Total
Non renewable, fossil	MJ-Eq	107,977
Non-renewable, nuclear	MJ-Eq	10,370
Renewable, biomass	MJ-Eq	410
Renewable, wind, solar, geothermal	MJ-Eq	101
Renewable, water	MJ-Eq	2,070
Total		**120,928**

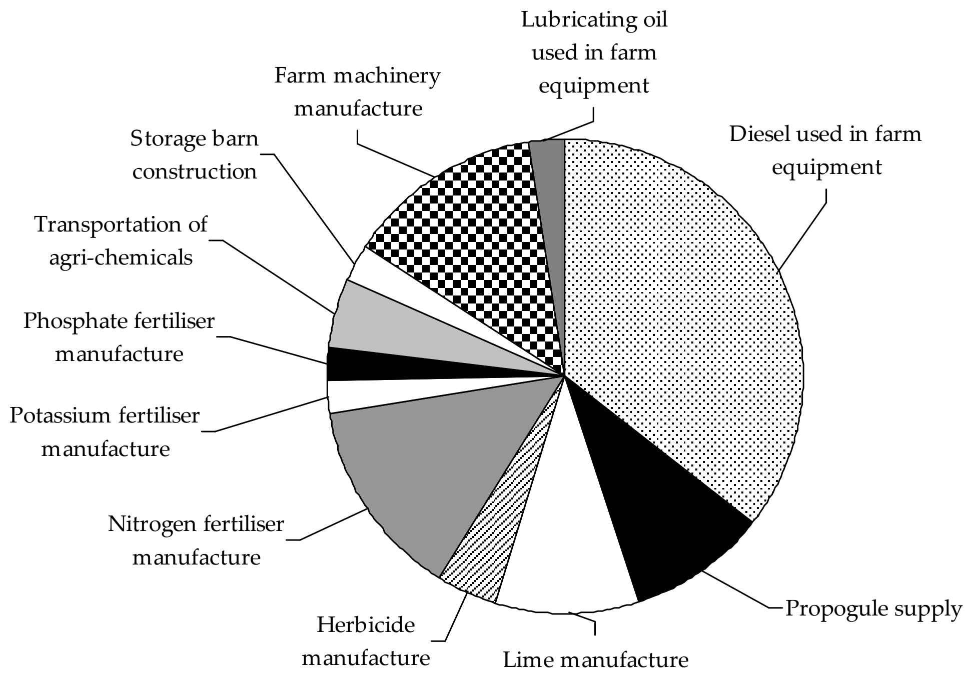


Figure 9-1: Percentage breakdown of calculated primary energy inputs for the cultivation of Miscanthus

The delivered energy output for Miscanthus is calculated as the total yield multiplied by the lower heating value (LHV), over the lifetime of the Miscanthus plantation. Assuming an annual harvest of 12 odt in years 3-18, and 6 odt in year 2 (see Chapter 6), and a LHV of 17.3MJ/kg, gives the total delivered energy output as 3,425GJ over 18 years. Once the first harvest is obtained in year 2, the delivered energy output is 103.8GJ. Even with a harvest of 50%, this is sufficient to payback the 34.7GJ consumed up to the first harvest in year 2. The energy payback period for Miscanthus is therefore only 2 years.

9.2.1.1. Net energy analysis results

Table 9-2 summarises the net energy analysis results for the cultivation of one hectare of Miscanthus over an 18 year lifetime. It should be noted that the ERE and EGR results are dimensionless and therefore also provide the result for 1kg or 1 tonne, etc. of Miscanthus. Comparative results for other biomass feedstocks are presented in section 9.5.1

Table 9-2: Net energy analysis results for the cultivation of Miscanthus

Result	Unit	Total	Comments
Delivered energy output	$MJ_{delivered}$	3,425,400	
Gross energy requirement (GER)	$MJ_{primary}$	120,928	
Energy Requirement of Energy (ERE)	$MJ_{primary}/MJ_{delivered}$	0.035	<1 means net energy is positive
Energy Gain Ratio (EGR)	$MJ_{delivered}/MJ_{primary}$	28.3	>1 means net energy is positive
Energy Payback Period (EPP)	Years	2	

9.2.1.2. Sensitivity analysis

A sensitivity analysis was performed on the GER to identify the parameters which had the largest effects on net energy analysis results. The sensitivity cases assessed for Miscanthus are taken from Chapter 6 table 10, with the main findings summarised as:

- Fertiliser applications have a significant impact on the GER, if N-fertiliser is applied annually the total GER increases by 70.7% (case G);
- Drying in industrial applications increases the total GER by 32.0% (case N);
- Irrigation significantly increases the total GER, by 94.8% with high amounts of water: 10,000m^3 per annum (case R).

The percentage change in the total GER is the same as the percentage change in the ERE, hence the EGR also changes proportionally in the opposite direction.

9.2.1.3. Effect of yield on results

The effect on net energy analysis results for a range of different yields is outlined in Table 9-3. The energy payback period will be 2 years for each yield due to the time required to establish and to obtain a sufficient first harvest to payback primary energy inputs.

Table 9-3: Effect on net energy analysis results for a range of different yields of Miscanthus

Yield (odt per year)	**8**	**9**	**10**	**11**	**12**	**13**	**14**
ERE	0.053	0.047	0.042	0.039	**0.035**	0.033	0.030
% change	*50.0%*	*33.3%*	*20.0%*	*9.1%*	**-**	*-7.7%*	*-14.3%*
EGR	18.9	21.2	23.6	26.0	**28.3**	30.7	33.0
% change	*-33.3%*	*-25.0%*	*-16.7%*	*-8.3%*	**-**	*8.3%*	*16.7%*

9.2.2 SRC Willow

Primary energy inputs for the production of one hectare of SRC Willow over a 23 year lifetime were calculated using CED. A GER of 234.4 GJ was calculated for the total primary energy inputs during the complete life cycle of SRC Willow cultivation. The breakdown by each energy source is shown in Table 9-4 and by field operation in Figure 9-2.

Table 9-4: GER by energy source for one hectare of SRC Willow over 23 year lifetime

Impact category	**Unit**	**Total**
Non renewable, fossil	MJ-Eq	208,116
Non-renewable, nuclear	MJ-Eq	19,151
Renewable, biomass	MJ-Eq	3,604
Renewable, wind, solar, geothermal	MJ-Eq	292
Renewable, water	MJ-Eq	3,197
Total		**234,361**

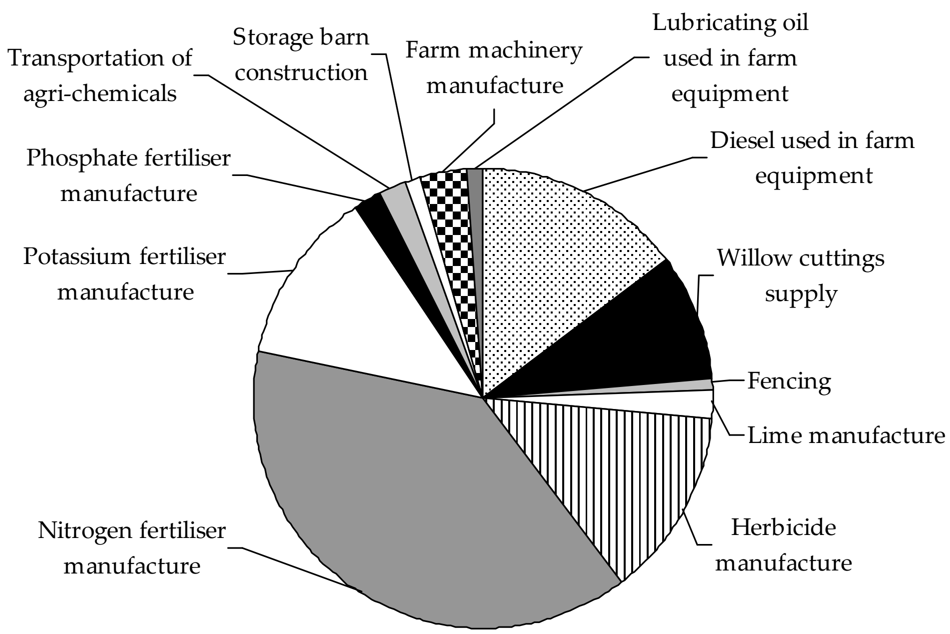


Figure 9-2: Percentage breakdown of the calculated primary energy inputs for the cultivation of SRC Willow

The delivered energy output for SRC Willow is calculated as the total yield multiplied by the lower heating value (LHV), over the lifetime of the SRC plantation. Assuming a harvest every 3 years of 24 odt, equivalent to 8 odt per annum (see Chapter 6), and a LHV of 18.3MJ/kg, gives the total delivered energy output as 3,074GJ over 23 years. Once the first harvest is obtained in year 4, the delivered energy output is 439.2GJ. This is sufficient to payback the 87.6GJ consumed up to the first harvest in year 4. The energy payback period for SRC Willow is therefore 4 years.

9.2.2.1. Net energy analysis results

Table 9-5 summarises the net energy analysis results for the cultivation of one hectare of SRC Willow over a 23 year lifetime. Again the ERE and EGR results are dimensionless and therefore also provide the result for 1kg or 1 tonne, etc. of SRC Willow. Comparative results for other biomass feedstocks are presented in section 9.5.1

Table 9-5: Net energy analysis results for the cultivation of SRC Willow

Result	Unit	Total	Comments
Delivered energy output	$MJ_{delivered}$	3,074,400	
Gross energy requirement (GER)	$MJ_{primary}$	234,361	
Energy Requirement of Energy (ERE)	$MJ_{primary}/MJ_{delivered}$	0.076	<1 means net energy is positive
Energy Gain Ratio (EGR)	$MJ_{delivered}/MJ_{primary}$	13.1	>1 means net energy is positive
Energy Payback Period (EPP)	Years	4	

9.2.2.2. Sensitivity analysis

A sensitivity analysis was performed on the GER to identify the parameters which had the largest effects on net energy analysis results. The sensitivity cases assessed for SRC Willow are taken from Chapter 6 table 10, with the main findings summarised as:

- Fertiliser applications have an impact on the total GER, if high amounts of N-fertiliser are applied the GER increases by 18.8% (case G);
- Drying in industrial applications increases the total GER by 11.0% (case N);
- Irrigation significantly increases the total GER, by 48.9% with high amounts of water: 10,000m^3 per annum (case R).

The percentage change in the total GER is the same as the percentage change in the ERE, hence the EGR also changes proportionally in the opposite direction.

9.2.2.3. Effect of yield on results

The effect on net energy analysis results for a range of different yields is outlined in Table 9-6. The energy payback period will be 4 years for each yield due to the time required to establish and to obtain a sufficient first harvest to payback primary energy inputs.

Table 9-6: Effect on net energy analysis results for a range of different yields of SRC Willow

Yield (odt per year)	**6**	**7**	**8**	**9**	**10**	**11**	**12**
ERE	0.102	0.087	0.076	0.068	0.061	0.055	0.051
% change	33.3%	14.3%	0%	-11.1%	-20.0%	-27.3%	-33.3%
EGR	9.8	11.5	13.1	14.8	16.4	18.0	19.7
% change	-25.0%	-12.5%	0.0%	12.5%	25.0%	37.5%	50.0%

9.3 BIOMASS GASIFICATION SYSTEM

The system boundary for the net energy analysis of the biomass gasification system is the same as the LCA study, as described in chapters 7 & 8. Data obtained in the LCI is therefore adequate to perform the net energy analysis. Primary energy inputs for the production of 1MJ of energy were calculated using Cumulative Energy Demand (CED). Biomass production and transportation are not included in this case study, but instead are assessed in the following section (9.4). Using waste on site will therefore produce more favourable net energy results than producing and transporting biomass from off-site.

9.3.1 Gross Energy Requirement (GER)

9.3.1.1. Plant construction

As a first step, it was necessary to calculate the primary energy inputs associated with the plant construction. The GER was calculated as 1,988.5GJ for the construction of the biomass gasification plant, with the breakdown shown in Table 9-7:

Table 9-7: GER for the construction the biomass gasification plant by energy source and plant component

	Non-renewable			Renewable		
Plant component	**Fossil**	**Nuclear**	**Biomass**	**Wind, solar, geothermal**	**Water**	**Total**
Unit	**GJ-Eq**	**GJ-Eq**	**GJ-Eq**	**GJ-Eq**	**GJ-Eq**	**(GJ-Eq)**
Outside enclosure	313.3	69.5	4.0	1.3	26.5	**414.7**
Steel structure	483.9	106.3	6.2	1.9	40.8	**639.0**
Wood feed system	73.1	8.1	0.6	0.1	2.0	**84.0**
Gasifier	111.1	24.6	1.4	0.4	7.4	**145.0**
Gas scrubber	51.8	11.1	0.6	0.2	4.3	**68.1**
Aftercooler & demister	30.2	6.2	0.4	0.1	2.4	**39.3**
Heat Exchanger	32.0	6.4	0.4	0.1	1.7	**40.6**
Instruments	38.7	9.5	0.3	0.1	6.9	**55.4**
Gas engine	406.1	71.8	2.5	0.8	21.3	**502.5**
Total	**1,540.2**	**313.6**	**16.4**	**5.0**	**113.2**	**1,988.5**

This gives the embodied energy associated with plant construction, which is defined as the total (direct and indirect) energy required in constructing the plant. This is a so-called 'sunk' energy cost which is consumed before the plant becomes operational, and is therefore a constant amount. To convert this into a 'per MJ of energy produced' basis, it is necessary to divide by the total energy output of the plant over its entire lifetime.

9.3.1.2. Plant operation

Primary energy inputs included in the net energy analysis of plant operation included: the embodied energy of the plant construction; energy consumed in wood-chipping; natural gas consumed at start-up; the parasitic electricity load of the plant; energy required in water supply, ash disposal and lubricating oil. These inputs for the plant operation are directly proportional to the number of hours the plant operates for, and therefore vary with the number of operating hours. The only exception to this is with natural gas consumption, which depends on the number of start-ups and is this therefore not directly related to the operating hours. Results for the GER for 1MJ of energy were calculated using the following assumptions:

- Gross electrical output is 918MJ/hour (255kW$_e$)
- Maximum heat output from plant is 1,800MJ/hour (500kW$_{th}$), however, actual delivered useful heat will vary with demand;
- Plant operates for between 1,000 and 7,000 a year over a 20 year lifetime (with 2,500 hours as the base case);
- There are 100 start-ups in the year.

The GER for the production of 1 hour of electricity production (0% heat demand) is displayed in Table 9-8 using the assumptions outlined above. This gives the GER for the gross electrical output of 918MJ/hour (255kW$_e$) assuming there is no demand for the heat. The results provided are to illustrate the relative primary energy inputs per hour of operation. With an increased heat demand the results for the GER would clearly reduce as the delivered energy output improved.

Table 9-8: GER for the production of 918MJ/hour (255kW$_e$) of electricity by energy source and operation stage

	Non-renewable		Renewable			
Operation stage	**Fossil**	**Nuclear**	**Biomass**	**Wind, solar, geothermal**	**Water**	**Total**
Unit	**MJ-Eq**	**MJ-Eq**	**MJ-Eq**	**MJ-Eq**	**MJ-Eq**	**(MJ-Eq)**
Plant construction	30.80	6.27	0.33	0.10	2.26	**39.77**
Waste wood chips	31.06	19.16	0.70	0.36	2.18	**53.46**
Tap water	0.24	0.13	0.02	0.00	0.02	**0.41**
Ash disposal	0.19	0.02	0.00	0.00	0.00	**0.20**
Waste water	0.19	0.13	0.00	0.00	0.03	**0.35**
Lubricating oil	1.91	0.06	0.00	0.00	0.01	**1.99**
Natural gas burnt	12.62	0.01	0.00	0.00	0.00	**12.63**
Electricity (UK mix)	22.74	7.67	0.00	0.08	0.17	**30.67**
Electricity (Internal)	0.00	0.00	81.00	0.00	0.00	**81.00**
Total	**99.76**	**33.45**	**82.06**	**0.55**	**4.67**	**220.49**

9.3.2 Delivered energy output

Electrical output from the plant is constant whilst the plant is running. All renewable electricity produced by the plant will either be consumed on site or fed back into the grid, as it is assumed that there is sufficient demand for the electricity. This means that in the net energy analysis the gross delivered electrical output per hour will remain the same for each hour of operation. Hence, the delivered primary energy will be 918MJ/hour (255kW$_e$) minus any transmission and distribution losses to the point of delivery. However, since the electricity is likely to be consumed locally distribution losses are assumed to be negligible.

Thermal (heat) output from the plant is approximately 1,800MJ/hour (500kW$_{th}$). This is considerable and if sufficient demand existed for this amount of heat, then it could provide 4.5TJ (1.25GWh$_{th}$) of heat per year. Unfortunately it is unlikely that there will be sufficient demand for this amount of heat throughout the year due to the seasonal variations in weather. In net energy analysis it is the 'delivered' energy which is accounted for. Therefore, it was considered appropriate to assess several potential scenarios of delivered heat, based on different levels of demand. Five scenarios for heat demand were selected which ranged from no demand, and each quartile up to full demand, i.e. 0%, 25%, 50%, 75% and 100%. These were selected to analyse how net energy analysis results would change according to the full range of demand for heat. Another important variable in the net energy analysis is the number hours the plant operates for each year, so this was also included in the main results. The minimum number of operating hours required for the plant to remain economical is 1,000 hours, and the maximum number assumed possible is 7,000. These values give the capacity factor in the range of 11.4% up to 79.9%.

9.3.3 Energy Requirement of Energy

Using the data outlined in sections 9.3.1 and 9.3.2, the ERE for 1MJ of energy produced from the biomass gasification system was calculated. The results for the ERE for the different operating hours and heat demand scenarios are displayed in Table 9-9. Comparative results for other technologies and net energy analysis studies are presented in section 9.5.

Table 9-9: ERE for the production of 1 MJ of energy from biomass gasification

	Energy Output	**Annual Operating hours**				
Heat demand scenario		**1000**	**2500**	**4000**	**5500**	**7000**
0% heat	$1MJ_e$ & $0MJ_{th}$	0.305	0.240	0.224	0.217	0.212
25% heat	$1MJ_e$ & $0.49MJ_{th}$	0.205	0.161	0.150	0.145	0.143
50% heat	$1MJ_e$ & $0.98MJ_{th}$	0.154	0.121	0.113	0.109	0.107
75% heat	$1MJ_e$ & $1.47MJ_{th}$	0.124	0.097	0.091	0.088	0.086
100% heat	$1MJ_e$ & $1.96MJ_{th}$	0.103	0.081	0.076	0.073	0.072

9.3.4 Energy Gain Ratio

Using the data outlined in sections 9.3.1 and 9.3.2, the EGR for 1MJ of energy produced from the biomass gasification system was calculated. The results for the EGR for the different operating hours and heat demand scenarios are displayed in Table 9-10. Comparative results for other technologies and net energy analysis studies are presented in section 9.5.

Table 9-10: EGR for the production of 1 MJ of energy from biomass gasification

	Energy Output	**Annual Operating hours**				
Heat demand scenario		**1000**	**2500**	**4000**	**5500**	**7000**
0% heat	$1MJ_e$ & $0MJ_{th}$	3.28	4.16	4.47	4.62	4.71
25% heat	$1MJ_e$ & $0.49MJ_{th}$	4.88	6.20	6.65	6.88	7.02
50% heat	$1MJ_e$ & $0.98MJ_{th}$	6.49	8.24	8.84	9.14	9.32
75% heat	$1MJ_e$ & $1.47MJ_{th}$	8.09	10.28	11.03	11.41	11.63
100% heat	$1MJ_e$ & $1.96MJ_{th}$	9.70	12.32	13.22	13.67	13.94

These results show that for the minimum operating hours of 1000, and no heat demand, the EGR is 3.28. This essentially means that in the worst case scenario 3.28MJ of energy will be generated for every 1MJ of primary energy input. For the base case of 2,500 operating hours the EGR improves to 4.16 with no heat, and 12.32 if all of the heat is utilised. The best case scenario is an EGR of 13.94 when the plant utilises 100% of the heat and operates for 7,000 hours a year. It is apparent from these findings that it is more important to utilise the heat than to increase operating hours, in terms of net energy benefit. Figure 9-3 portrays the EGR results for the range of heat demand scenarios and operating hours.

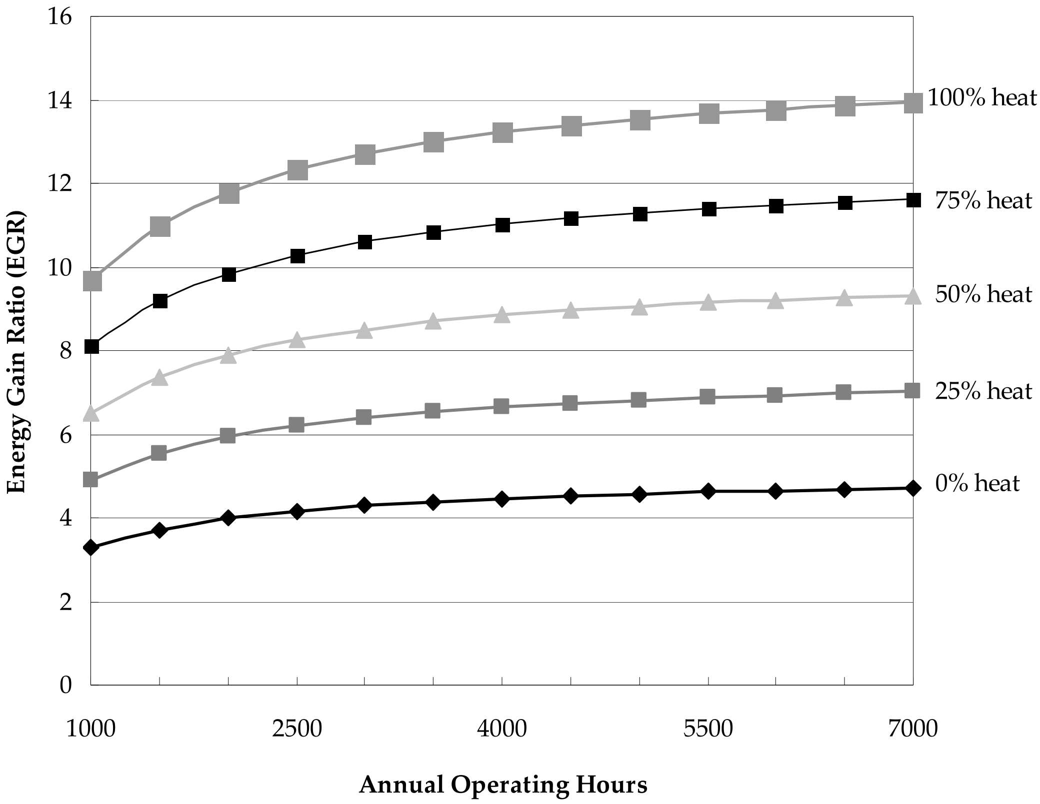


Figure 9-3: EGR for the production of 1 MJ of energy from biomass gasification

9.3.5 Energy Payback Period

To calculate the EPP for the biomass gasification plant, the starting point is the embodied energy associated with plant construction. Once the plant starts operating, the delivered energy output is high in comparison with the primary energy inputs, as demonstrated by both the ERE and the EGR. The EPP is the length of time that it takes for the net energy produced by the plant (i.e. delivered energy output minus operational primary energy inputs) to break-even. In other words it is the period of operation required to payback the embodied energy of the plant construction. Table 9-11 summarises the EPP for different energy outputs and operating hours.

Table 9-11: Energy payback period (in years) for the biomass gasification plant

	Energy Output	**Annual Operating hours**				
Heat demand scenario		**1000**	**2500**	**4000**	**5500**	**7000**
0% heat	$1MJ_e$ & $0MJ_{th}$	2.70	1.08	0.67	0.49	0.39
25% heat	$1MJ_e$ & $0.49MJ_{th}$	1.68	0.67	0.42	0.30	0.24
50% heat	$1MJ_e$ & $0.98MJ_{th}$	1.21	0.49	0.30	0.22	0.17
75% heat	$1MJ_e$ & $1.47MJ_{th}$	0.95	0.38	0.24	0.17	0.14
100% heat	$1MJ_e$ & $1.96MJ_{th}$	0.78	0.31	0.20	0.14	0.11

It was found that the plant has an energy payback of less than 2.7 years even when the heat is not utilised and operates for the minimum time of 1,000 hours. For 2,500 operating hours, the energy payback is one year and a month when the heat is not utilised. This improves to less than one year when 4% or more of the heat is consumed. If the plant utilises all of the heat produced and operates for the 7,000 hours a year then the best possible EPP is just 41 days (0.11 years). In all heat demand scenarios the break-even point is less than one year when approximately 2,750 operating hours or more are utilised. Figure 9-4 portrays the EGR results for the range of heat demand scenarios and operating hours.

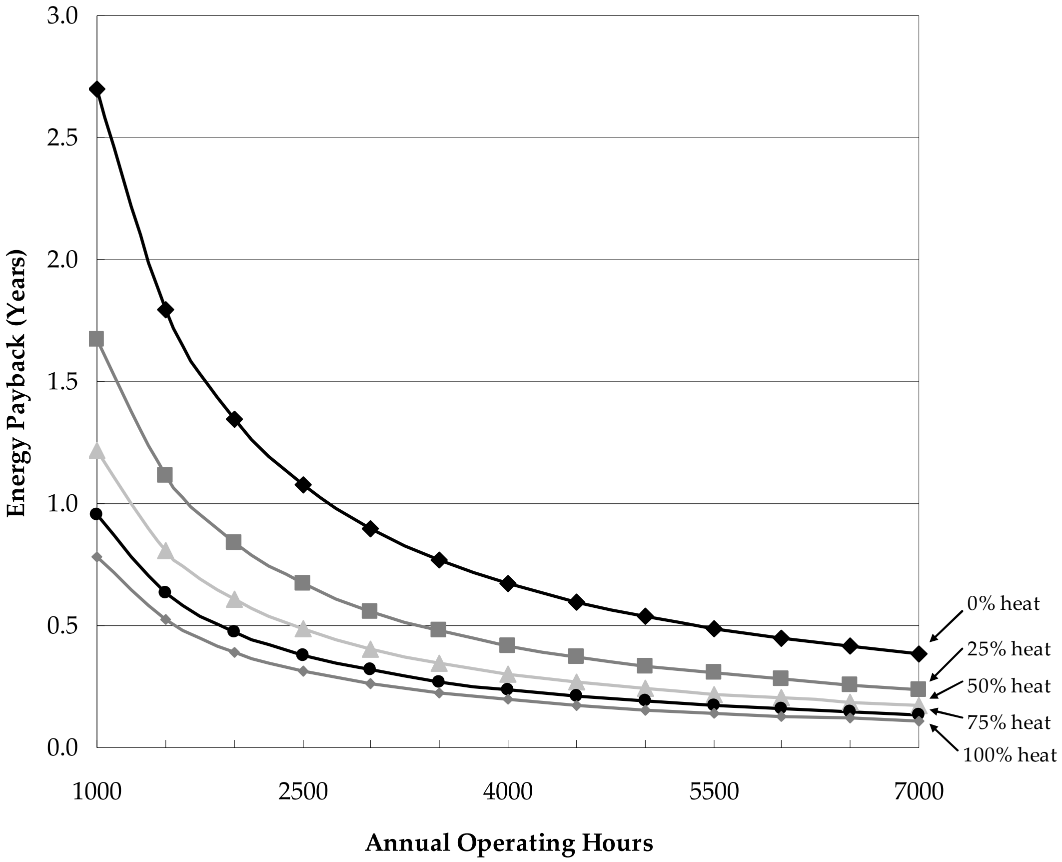


Figure 9-4: EPP for the production of 1 MJ of energy from biomass gasification

9.3.6 Displaced energy

In this biomass gasification CHP plant case study, the energy produced can displace other energy-supply technologies. It is anticipated that the electricity generated will directly displace electricity supplied by the UK grid. Similarly, the heat generated can displace the need for a natural gas boiler. To calculate the 'displaced energy' it is first necessary to compute the GER for the energy-supply technology which is being displaced. For the UK electricity grid, the data obtained in Table 7-6 was used to compute the GER; the results are shown in Table 9-12.

Table 9-12: GER per MJ_e by energy source for the UK electricity grid (calculated using CED and data from DECC, 2009a; Swiss Centre for Life Cycle Inventories, 2009)

Primary energy source	Unit	Total
Non renewable, fossil	MJ-Eq	2.389
Non-renewable, nuclear	MJ-Eq	0.490
Renewable, biomass	MJ-Eq	0.001
Renewable, wind, solar, geothermal	MJ-Eq	0.021
Renewable, water	MJ-Eq	0.018
Total		**2.920**

For heat produced via a natural gas condensing boiler, primary energy input data was obtained from the Ecoinvent database. The GER was then calculated using CED, which gave the following results (see Table 9-13).

Table 9-13: GER per MJ_{th} by energy source for heat produced by a natural gas boiler (calculated using CED and data from Swiss Centre for Life Cycle Inventories, 2009)

Primary energy source	Unit	Total
Non renewable, fossil	MJ-Eq	1.223
Non-renewable, nuclear	MJ-Eq	0.007
Renewable, biomass	MJ-Eq	0.000
Renewable, wind, solar, geothermal	MJ-Eq	0.000
Renewable, water	MJ-Eq	0.002
Total		**1.233**

Having computed the GER for both UK grid electricity and heat from a natural gas boiler, it was then possible to calculate some displaced energy metrics. Various results were produced, including different energy system displacement scenarios, for example:

- Displacement of UK grid electricity only;
- Displacement of heat from natural gas boiler only;
- Displacement of both UK grid electricity and heat from natural gas boiler.

Each of these scenarios was calculated alongside the different possible heat demand situations. In the first scenario, when just the UK grid electricity is displaced, for every MJ of electricity produced from the biomass gasification plant, 2.92MJ of primary energy is displaced from the UK grid (see Table 9-12). In the second scenario, when just heat is displaced, the outcome depends on the heat demand. For every 1MJ of heat demand, 1.233MJ of primary energy is displaced. This implies that more primary energy will be displaced when the UK electricity grid is the alternative energy-supply system. Nonetheless, higher heat demand means that the results are more comparable, i.e. if 100% of the heat is utilised 2.42MJ (1.233 * 1.96MJ_{th}) of heat will be displaced.

Perhaps the most realistic scenario is when both electricity and heat are displaced, which is the clear benefit of CHP. To illustrate the results for displaced energy, the scenario of 100% electricity and 50% heat utilisation were chosen. This generates 1MJ_e & 0.98MJ_{th} and will therefore displace the equivalent of 1MJ_e of UK grid electricity (i.e. 2.92MJ of primary energy) and 0.98MJ_{th} of heat from a natural gas boiler (i.e. 1.21MJ of primary energy). Results for the EGR and EPP are presented in Figure 9-5 and Figure 9-6 respectively, for the range of different operating hours.

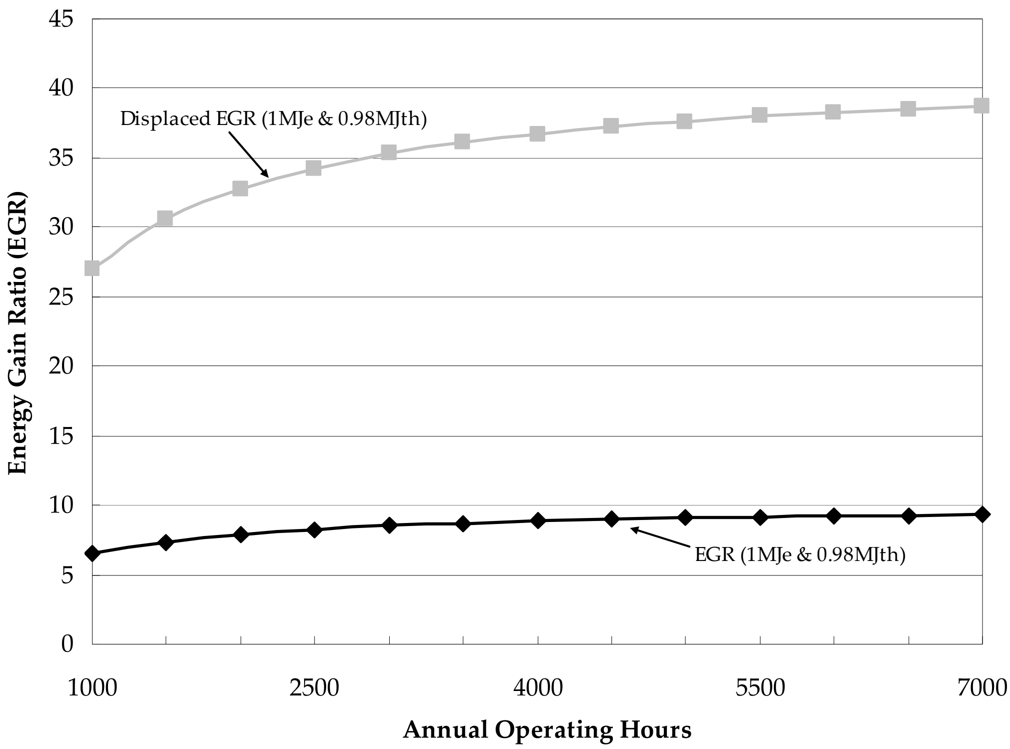


Figure 9-5: Displaced EGR for the production of 1 MJe & 0.98MJth from biomass gasification

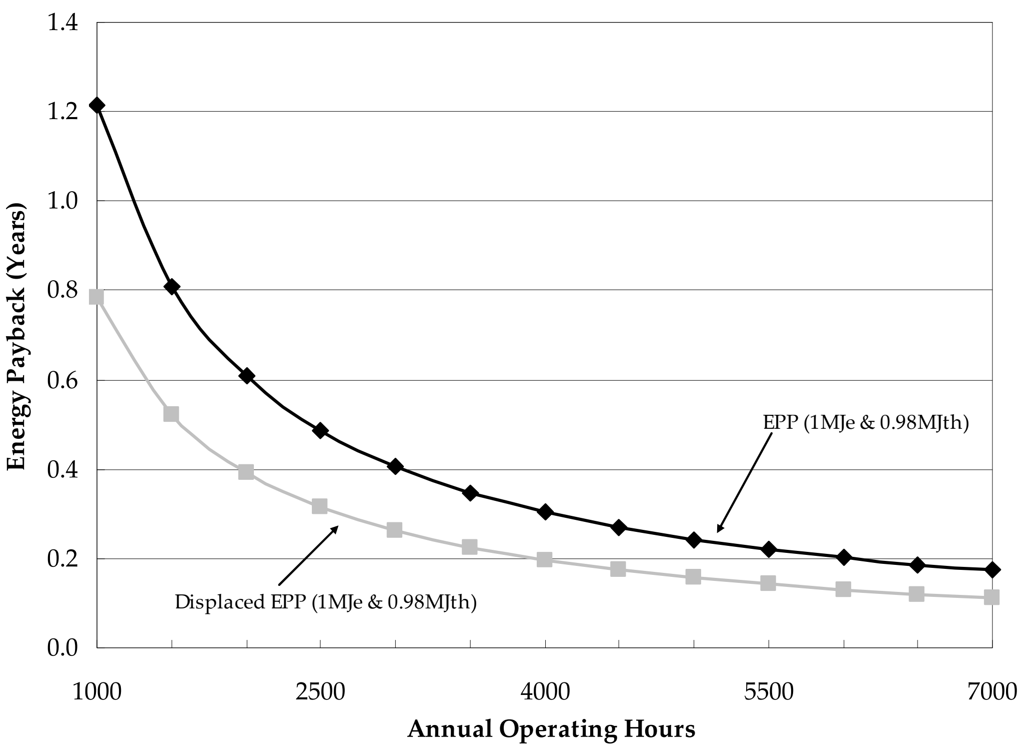


Figure 9-6: Displaced EPP for the production of 1 MJe & 0.98MJth from biomass gasification

9.4 BIOENERGY SYSTEM SCENARIOS

Net energy analysis results presented in section 9.3 are based on the biomass gasification CHP plant case study. As this plant uses wood waste produced on site by a furniture factory, there is no biomass crop growth or transportation involved. However, for many bioenergy systems these will be integral parts of the energy supply chain. In chapter 5 it was shown that the utility of biomass gasification is ultimately resource limited. The growth of dedicated energy crops is thus likely to play an important role in future biomass supply chains. This section therefore assesses the effect of biomass cultivation and transportation on the net energy analysis results.

To analyse the different bioenergy system scenarios, it was first necessary to calculate the GER for each aspect of the supply chain. The main parts of the supply chain considered were biomass cultivation and transportation. Other aspects may include irrigation, drying, biomass processing, as considered in the sensitivity analysis.

9.4.1 Gross energy requirement

The GER for each additional aspect of the supply chain was calculated using Cumulative Energy Demand (CED). Biomass cultivation and transportation are described here.

9.4.1.1. Biomass cultivation

The GER for biomass cultivation was calculated in section 9.2 for Miscanthus and SRC Willow. It was considered more appropriate to use Willow for this biomass gasification plant (BGP) system expansion scenario, as it is a woody feedstock. The BGP was designed using wood as a feedstock and there are also very limited examples in the literature of Miscanthus being gasified. Hence the GER of 1.4MJ/kg of Willow (or ERE of 0.076), as calculated in section 9.2.2, was used for biomass cultivation in this case study.

As the BGP requires 200kg of feedstock per hour, for the base case of 2,500 hours, 500 odt of Willow will be required per annum. With a harvest every 3 years of 24 odt, equivalent to 8 odt per annum (see Chapter 6), approximately 62.5 hectares of SRC Willow will be required. An area of 5% of farmland is assumed to be used for perennial energy crops, as this density could be viable without significantly impacting on food production (DEFRA, 2007a). This 5% assumption is based on the UK Biomass Strategy, as 350,000 ha is ~5% of the total UK cropland, bare fallow, temporary grassland and previous set-aside.

9.4.1.2. Transportation

Once the biomass is harvested it will need to be transported to a central point where the BGP is located. The transportation distance will depend on such factors as the size of the plant, location of the biomass, density of the energy crop plantations, and directness of the roads. With this case study, the size of the plant is known, so it is possible to calculate the transportation distance using assumptions for the other factors.

The number of hectares available around a BGP can be estimated by taking the radius of a circle and calculating the area. For example, a 5km radius around the BGP will have a total of 7,854 ha of land within 5km. This assumes the area of a circle equals πr^2 and there are 100 ha in 1km^2. However not all of this land will be available for crop production. In the case of the South West of England, approximately 75% of the land is farmland, 27% of the farmland is cropland and 11% of the farmland is temporary grassland (see Table 5-2). This implies that 28.5% of land could be available for energy crop production. Another factor to consider is the density of plantations; it is likely that only small percentages of farmland will be used to cultivate energy crops. Table 9-14 displays the calculated number of hectares available for energy crops for different distances and plantation densities, based on average South West land use.

Table 9-14: Number of hectares of land available for energy crop plantations at different distances from biomass conversion plant

Distance from plant (km)	Total land available (ha)	Total farmland (75% of total) (ha)	Total cropland & temp. grassland (38% of farmland) (ha)	Energy crop plantation density (ha)			
				1%	2%	5%	10%
1	314	236	90	0.9	1.8	4.5	9.0
2	1,257	942	358	3.6	7.2	17.9	35.8
3	2,827	2,121	806	8.1	16.1	40.3	80.6
4	5,027	3,770	1,433	14.3	28.7	71.6	143.3
5	7,854	5,890	2,238	22.4	44.8	111.9	223.8
10	31,416	23,562	8,954	89.5	179.1	447.7	895.4
20	125,664	94,248	35,814	358.1	716.3	1,791	3,581
40	502,655	376,991	143,257	1,433	2,865	7,163	14,326

Finally the indirectness of roads should be accounted for when calculating transportation distance, as not all roads can be considered to be straight. When biomass is transported short distances the roads are likely to be less direct, whereas for long distances motorways can be used which are more direct. A review of some existing bioenergy systems found that on average 20-30% can be added onto the 'direct', or as the bird flies, distance. For this study a factor of 25% was added onto the direct distance to give the 'effective' distance. This is also known as a tortuosity factor (Thornley, 2008).

Using the data calculated in Table 9-14 and a 5% plantation density, it can be seen that the 62.5 ha required can be located within 4km of the BGP. Adding on the effective distance factor of 25% gives a total distance of 5km, and a round-trip of 10km. A EURO3 lorry with a maximum load capacity of 12 tonnes was selected from the Ecoinvent database for transporting the biomass. This lorry was selected as it is the most common type in operation in Europe and the size is most appropriate for biomass transportation. Due to the bulk density of Willow, only 10 tonnes are assumed to be transported with each trip. A total of 50 trips are therefore required each year to transport the 500 odt per annum.

To calculate the GER for transportation by lorry, the concept of tonne-kilometres (tkm) is used. This unit of measurement represents the transport of one tonne of biomass over one kilometre. Data on the lorry (construction, operation & maintenance), road (construction & maintenance), and disposal were obtained from the Ecoinvent database. These datasets were combined to calculate the GER for one tkm (see Table 9-15) for a EURO3 12 tonne lorry. An additional assumption is that the lorry will drive to the BGP with a full load, and back to the farm with an empty load.

Table 9-15: GER per tonne-kilometre for a EURO3 12 tonne lorry (calculated using CED and data from Swiss Centre for Life Cycle Inventories, 2009)

Primary energy source	**Unit**	**Total**
Non renewable, fossil	MJ-Eq	4.427
Non-renewable, nuclear	MJ-Eq	0.252
Renewable, biomass	MJ-Eq	0.007
Renewable, wind, solar, geothermal	MJ-Eq	0.002
Renewable, water	MJ-Eq	0.048
Total		**4.735**

Total primary energy for transportation was calculated using the data above as 23,677MJ-Eq per annum, which is easily converted into per hour or per MJ energy generated.

9.4.2 Energy Requirement of Energy

Using the additional data for biomass cultivation and transportation (outlined in section 9.4.1) and the data for plant construction and operation, the ERE for this scenario was calculated. It was found that the ERE increased by more than 100% for all heat demand and operating hours situations (see Table 9-16).

Table 9-16: ERE for the production of 1 MJ of energy from biomass gasification with energy crop cultivation and transportation

	Energy Output	**Annual Operating hours**				
Heat demand scenario		**1000**	**2500**	**4000**	**5500**	**7000**
0% heat	$1MJ_e$ & $0MJ_{th}$	0.614	0.549	0.533	0.526	0.522
25% heat	$1MJ_e$ & $0.49MJ_{th}$	0.412	0.369	0.358	0.353	0.350
50% heat	$1MJ_e$ & $0.98MJ_{th}$	0.310	0.278	0.269	0.266	0.263
75% heat	$1MJ_e$ & $1.47MJ_{th}$	0.249	0.222	0.216	0.213	0.211
100% heat	$1MJ_e$ & $1.96MJ_{th}$	0.208	0.186	0.180	0.178	0.176

9.4.3 Energy Gain Ratio

The EGR was calculated to account for both biomass cultivation and transportation, using the same data as the ERE. It was found that the EGR decreased by more than 50% for all heat demand and operating hours situations (see Table 9-17).

Table 9-17: EGR for the production of 1 MJ of energy from biomass gasification with energy crop cultivation and transportation

	Energy Output	**Annual Operating hours**				
Heat demand scenario		**1000**	**2500**	**4000**	**5500**	**7000**
0% heat	$1MJ_e$ & $0MJ_{th}$	1.63	1.82	1.88	1.90	1.92
25% heat	$1MJ_e$ & $0.49MJ_{th}$	2.42	2.71	2.79	2.83	2.86
50% heat	$1MJ_e$ & $0.98MJ_{th}$	3.22	3.60	3.71	3.77	3.80
75% heat	$1MJ_e$ & $1.47MJ_{th}$	4.02	4.50	4.63	4.70	4.74
100% heat	$1MJ_e$ & $1.96MJ_{th}$	4.82	5.39	5.55	5.63	5.67

Figure 9-7 shows that the EGR results are much more favourable when wood waste is used on site. Biomass cultivation and transportation reduce the EGR to less than 4 $MJ_{delivered}$/ $MJ_{primary}$ when 50% of the heat is utilised.

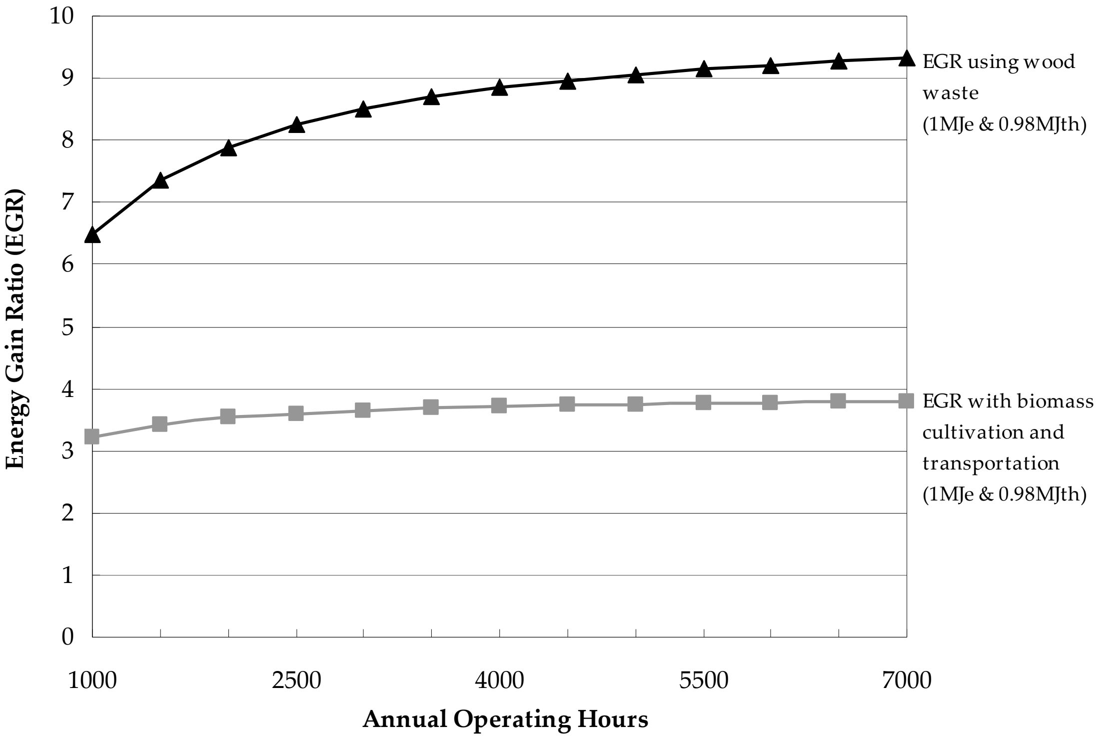


Figure 9-7: Comparison of the EGR results for the production of 1 MJe & 0.98MJth from biomass gasification (with and without biomass cultivation and transportation)

9.4.4 Energy Payback Period

When biomass cultivation is involved the energy payback period increases significantly due to the time taken to establish SRC Willow plantations. It is 4 years before the first harvest of Willow, thus the EPP is much higher when dedicated energy crops are grown for the biomass supply (see Table 9-18).

Table 9-18: Energy payback period (in years) for the biomass gasification plant with energy crop cultivation and transportation

	Energy Output	**Annual Operating hours**				
Heat demand scenario		**1000**	**2500**	**4000**	**5500**	**7000**
0% heat	$1MJ_e$ & $0MJ_{th}$	8.39	5.75	5.10	4.80	4.63
25% heat	$1MJ_e$ & $0.49MJ_{th}$	6.20	4.88	4.55	4.40	4.31
50% heat	$1MJ_e$ & $0.98MJ_{th}$	5.47	4.59	4.37	4.27	4.21
75% heat	$1MJ_e$ & $1.47MJ_{th}$	5.10	4.44	4.28	4.20	4.16
100% heat	$1MJ_e$ & $1.96MJ_{th}$	4.88	4.35	4.22	4.16	4.13

9.5 COMPARISON TO OTHER NET ENERGY ANALYSIS STUDIES

A review of previous related studies was performed to compare the findings of this study with other results. This included a review of crop growth and biomass gasification, but also other bioenergy and fossil fuel reference systems. In this section a summary of the more important and relevant related studies are provided to put the results in the context of other crop and energy production systems.

9.5.1 Crop growth

9.5.1.1. Miscanthus

In a study for the DTI, Bullard & Metcalfe (2001) calculated the energy gain ratio (EGR) for the cultivation of Miscanthus as 35.9. This is slightly higher than the EGR calculated in this study of 28.3. The difference can be explained primarily by a LHV of 18MJ/kg and a yield of 18odt/ha being used by Bullard & Metcalfe (2001), which clearly results in a higher delivered energy output. Other smaller differences relate to the GER, with different data sources and assumptions being used in this study. In another study, Elsayed *et al.* (2003) found the EGR for Miscanthus to be approximately 45 Lewandowski *et al*. (2000) suggest an EGR of between 14 and 20 which assumes an annual application of N-fertiliser of 100kg.

9.5.1.2. SRC Willow

There are more net energy analysis studies of SRC Willow than for Miscanthus. Perhaps the most well known study was performed by Matthews (2001) who calculated the EGR for the cultivation of SRC Willow as 26.7. This was much higher than in the present study due primarily to the assumptions surrounding fertiliser use and yields. Matthews (2001) assumed that N-fertiliser was only applied twice, whereas in this study it has been assumed to be applied after each harvest in line with local farming practices and DEFRA guidance. Additionally Matthews (2001) assumes a yield of 12odt/yr which is 50% higher than in this study. Another UK based study by Elsayed *et al.* (2003) suggests an EGR of approximately 25.6, but this uses several of the same assumptions as Matthews (2001).

Studies from other countries also give a range of results for the EGR of SRC Willow; these include: Sweden – 21 (Borjesson, 1996); USA – 11 (Heller *et al.*, 2003); USA – 55 (Keoleian and Volk, 2005); Belgium – 23 (Dubuisson & Sintzoff, 1998). These results vary principally depending on assumptions about yields and fertiliser inputs. It should be considered that localised growing conditions will affect the productivity and crop management regime.

9.5.1.3. Other perennial crops

Reed canary grass and switchgrass are other perennial crops which can be used for bioenergy production. Bullard & Metcalfe (2001) calculated an EGR of 20.4 for Reed canary grass and 28.9 for Switchgrass. Borjesson (1996) calculated an EGR for Reed canary grass of 11, whilst Boehmel *et al.* (2008) suggest an EGR for Switchgrass of 38. These other studies indicate that other perennial crops also have very positive energy gain ratios.

9.5.1.4. Annual crops

Gross energy requirements for annual crops were found to be much higher than perennial crops, due to higher agro-chemical inputs and that they are established on an annual basis. HGCA (2005) show that the fertiliser, pesticide, herbicide and insecticide applications are much higher in annual crops than the perennial energy crops studied here. Table 9-19 displays some brief net energy analysis findings for annual crops to demonstrate that the energy inputs are higher, and the energy yields and EGR are lower than perennial crops.

Table 9-19: Net energy analysis for selected annual crops

	Energy Inputs (MJ/ha)	Energy Yield (MJ/ha)	EGR
Wheat	19,171	102,000	5.3
Oilseed rape	12,689	66,300	5.2
Sugar beet	17,809	26,600	1.5
Source	HGCA, 2005	EEA, 2007	Calculated

9.5.2 Biomass Gasification

Elsayed *et al.* (2003) completed a comprehensive net energy analysis of several bioenergy production systems. In their study of biomass gasification using Willow, the EGR for electricity generation was calculated as 6.2, and when CHP was utilised the EGR was found to be 10.3. Carpentieri *et al*., (2005) calculated an ERE of 0.296 for a biomass gasification combined cycle system (BGCC), which is equivalent to an EGR of 3.4. In another study of a BGCC, an ERE of 0.064 was presented, equivalent to an EGR of 15.6, however this did not include the electricity consumed by the plant (Mann & Spath, 1997). Keoleian and Volk (2005) calculated an EGR of 12.8 and 13.3 for the gasification of SRC Willow. These results are of a similar magnitude as the present study.

9.5.3 Anaerobic Digestion

Net energy analysis results for biogas production were found to differ extensively. Results varied depending on where the system boundary is set and the AD plant setup, i.e. feedtock type, plant size, technology, operating parameters, conversion efficiency, etc. These aspects have a key effect on the energy analysis findings, in a similar way to biomass gasification. An EGR of between 0.42 and 1.67 was found in a study of large scale electricity biogas plants by (Borjesson & Berglund, 2006), which is similar to that of Mezzullo (2010) who found an EGR of between 0.70 and 1.42. When heat is the end-use of biogas, it gives an EGR of between 0.60 and 1.92 (Mezzullo, 2010). A result for CHP was not obtained for biogas but it is fair to assume this would improve the EGR of an AD plant.

The detailed studies undertaken reveal that the up to 80% of the energy input into the AD process is consumed by the plant itself (Borjesson & Berglund, 2006; Mezzullo, 2010). Within a typical AD plant the majority of the energy consumed is used to heat the digestor to enable the digestion process. Other aspects of the plant operation, such as electrical requirements for pumps, motors and mixing, have relatively low energy consumption. These results for AD may imply that biogas has limited potential but this is not the case. The EGR for AD is still very favourable when compared currently utilised fossil fuel resources. In addition the AD process can generate energy out of a waste product, which could other generate much higher methane emissions. The other added benefit which could be factored into the results is the organic fertiliser by-product. This can help offset the use of energy intensive inorganic fertilsers.

9.5.4 Other Bioenergy Pathways

Numerous studies have been undertaken on the net energy analysis of various different bioenergy pathways. A review of these studies shows that significant work has been completed in this area for biofuels for transport. Fewer results were found for biomass heat and power. A selection of these studies is summarised in Table 9-20. It is beyond the scope of this thesis to further describe the system boundaries and results from each of these studies. Nonetheless they provide a useful indication of how different pathways compare.

Table 9-20: EGR for selected bioenergy pathways

Generation technology	EGR ($MJ_{delivered}$ / $MJ_{primary}$)	Source
Electricity		
Combustion of Miscanthus (large scale)	3.7	Adapted from Elsayed *et al* ., 2003
Combustion of SRC Willow	2.7	
Pyrolysis of SRC Willow	3.1	
Gasification of SRC Willow	6.2	
Gasification of SRC Willow	12.8-13.3	Keoleian and Volk, 2005
Combustion of SRC Willow	9.9	
Anaerobic digestion	0.4-1.7	Borjesson & Berglund, 2006
Waste wood steam turbine	10	Pehnt, 2006
Short rotation forestry steam turbine	7.8	
Heat		
Anaerobic digestion	0.6-1.9	Mezzullo, 2010
Forest wood heating plant	16.4	Pehnt, 2006
Short rotation forestry heating plant	12.7	
Straw heating plant	15.2	
CHP		
Gasification of SRC Willow (small scale)	10.3	Adapted from Elsayed *et al* ., 2003
Short rotation forestry reciprocating engine	18.3	Pehnt, 2006
Forest wood reciprocating engine	27	
Anaerobic digestion	55.6	
Transport Fuel		
Bio-ethanol from wheat	~2.1	Elsayed *et al* ., 2003
Bio-diesel from oilseed rape	~2.3	
Bio-diesel from waste vegetable oil	~5.5	

9.5.5 Fossil Fuel Reference Systems

Table 9-21 displays the EGR for some selected electricity and heat generation technologies. For the biomass gasification plant, as the proportion of heat utilised increases so does the EGR, with analogous results for the EPP. In comparison to UK grid electricity, or a natural gas power plant (electricity only), the EGR is significantly higher. Likewise the EGR of the plant is also higher than either natural gas or light fuel oil used for heating only. This is partly due the energy required to extract and refine fossil fuels ready for use in power or heat production. Another factor which gives these other systems a lower EGR is that the energy content of the feedstock is counted as an energy input since its use results in the depletion of a non-renewable resource (Elsayed *et al.*, 2003). In comparison, the energy content of biomass feedstock is not accounted for as this is renewable energy resource.

Table 9-21: EGR for selected electricity and heat generation technologies

Generation technology	EGR ($MJ_{delivered}$ / $MJ_{primary}$)	Comments	Source
Current UK grid electricity	0.33	This is representative of the current UK electricity system	Calculated based on DECC, 2010b; (Swiss Centre for Life Cycle Inventories, 2009)
UK grid electricity	0.32	UK electricity system in 2003	Elsayed *et al.*, 2003
Natural gas electricity	0.43	Based on average of natural gas power only plants in the UK	(Swiss Centre for Life Cycle Inventories, 2009)
Natural gas heating	0.79	Based on natural gas burned in an industrial furnace (200 kW)	
Heavy fuel oil heating	0.74	Based on heavy fuel oil burned in an industrial furnace (1 MW)	
Diesel	0.79		Elsayed *et al.*, 2003
Petrol	0.84		

9.6 SUMMARY

The research performed in this chapter is important in showing how net energy analysis can be used to analyse the process chain of bioenergy systems. By analysing the different material and energy inputs it highlights which aspects are more energy intensive. It has established that the EGRs of the case studies in this thesis were all found to be positive and comparable to other biomass technologies. A crucial finding is that the EGRs which can be achieved have the ability to displace some fossil fuel sources. This means that although fossil fuel depletion was found to be a potential issue in the LCA, a very positive EGR could reduce the overall demand for fossil fuels.

For the perennial energy crops the EGRs were much higher than annual food crops. The Biomass gasification plant (BGP) using wood waste achieved an EGR of 4.16 when only electricity was utilised. This was found to increase to 12.32 when all of the useful heat and electricity is consumed. These results show that although fossil fuel depletion is an issue in crop growth, the energy content of the actual crop (i.e. the crop's net calorific value) has the potential to reduce some dependence on fossil fuels. When SRC Willow is used instead of wood waste (with associated transportation), the EGRs reduced to between 1.82 and 5.39, which shows that crop cultivation is a key consideration in the energy inputs to the bioenergy system. The effect of crop growth and transportation for other environmental impacts in the whole life cycle is now explored in Chapter 10.

CHAPTER 10. LIFE CYCLE ENVIRONMENTAL IMPACTS OF BIOENERGY SYSTEMS

This chapter brings together the results from Chapters 6 to 9 and expands the LCA study to assess the environmental effects of the full bioenergy supply chain. The logic behind this is to combine the LCA of perennial energy crops (see Chapter 6) with the LCA of the biomass gasification plant (see Chapters 7 & 8), to assess the relative contribution of the main aspects of the supply chain. Transportation of biomass is also included to follow the same system expansion as performed in the net energy analysis (see Chapter 9). The impact categories assessed in this LCA are limited to those identified as significant in the individual LCA studies. Results are then compared to previous LCAs of other energy production systems to provide a comparison of the potential environmental impacts from different energy sources.

From chapters 6 and 8 the main impact categories of concern to crop growth and biomass gasification were identified as climate change, human toxicity, terrestrial ecotoxicity, particulate matter formation, agricultural land occupation, metal depletion, and fossil resource depletion. Additionally, acidification and eutrophication are also potential issues where agro-chemical inputs are high. This chapter provides further analysis of the full bioenergy supply chain for each of these impact categories using ReCiPe (midpoint).

10.1 POTENTIAL LIFE CYCLE ENVIRONMENTAL IMPACTS OF BIOMASS GASIFICATION USING PERENNIAL ENERGY CROPS

For each impact category, the results from the base case for biomass gasification using wood waste (from Chapter 8) are analysed against the inclusion of crop growth, transport, and the main variables which effect the results. Findings are presented for the whole life cycle emissions. The following assumptions are used:

- Feedstock requirements for the biomass gasification plant (BGP) are 200kg of wood waste per hour, which is equivalent to 241.5kg per GJ of electricity produced. It assumed SRC Willow has the same NCV as the wood waste, but Miscanthus has a lower NCV, so a higher amount of feedstock will be required (~212kg per hour).
- Transport requirements are 50 trips per year at 10odt per load, which is equivalent to 0.0242 trips per GJ of electricity produced, slightly higher for Miscanthus (~0.0256). The distance travelled is assumed to be a 10km round-trip, as described in Chapter 9 section 4.

Each of these variables is used to calculate the results for the full bioenergy supply chain, i.e. the impacts associated with using wood waste are replaced with Miscanthus or SRC Willow, and transportation is included. Results from Chapters 6 for Miscanthus cultivation and SRC Willow are used, along with the plant construction and operation results from Chapter 8. The results are calculated using ReCiPe (midpoint) to reduce uncertainties in the life cycle impact assessment (LCIA) findings. LCIA results presented will change with different crop management techniques, transportation methods, biomass processing, etc. Therefore reference should be made to sensitivity analyses performed to highlight the main variables which affect the results.

10.1.1 Climate change

A predominant environmental benefit of biomass energy is its apparent carbon neutrality with respect to the atmosphere. The CO_2 emitted in using the biomass energy is balanced by the CO_2 absorbed in growing the biomass crop, resulting in no net increase in atmospheric CO_2. However, other sources of CO_2 emissions that exist in the system (tractor operation, fertiliser manufacturing, etc.) must be considered. In addition, emissions of other greenhouse gases, such as methane (CH_4), will also contribute to the net global warming potential of the system. It is these fossil-based emissions that are accounted for in this LCA study and biogenic emissions have so far been excluded.

Emissions of CO_2 eq. for crop cultivation and the BGP are taken from Chapters 6 and 8 respectively. Transportation emissions are assumed to be 0.29kg of CO_2eq. per tonne-km (see Appendix I). Results displayed in Figure 10-1 combine these findings and show the GHG emissions for the whole life cycle based on assumptions outlined in Chapters 6 to 9.

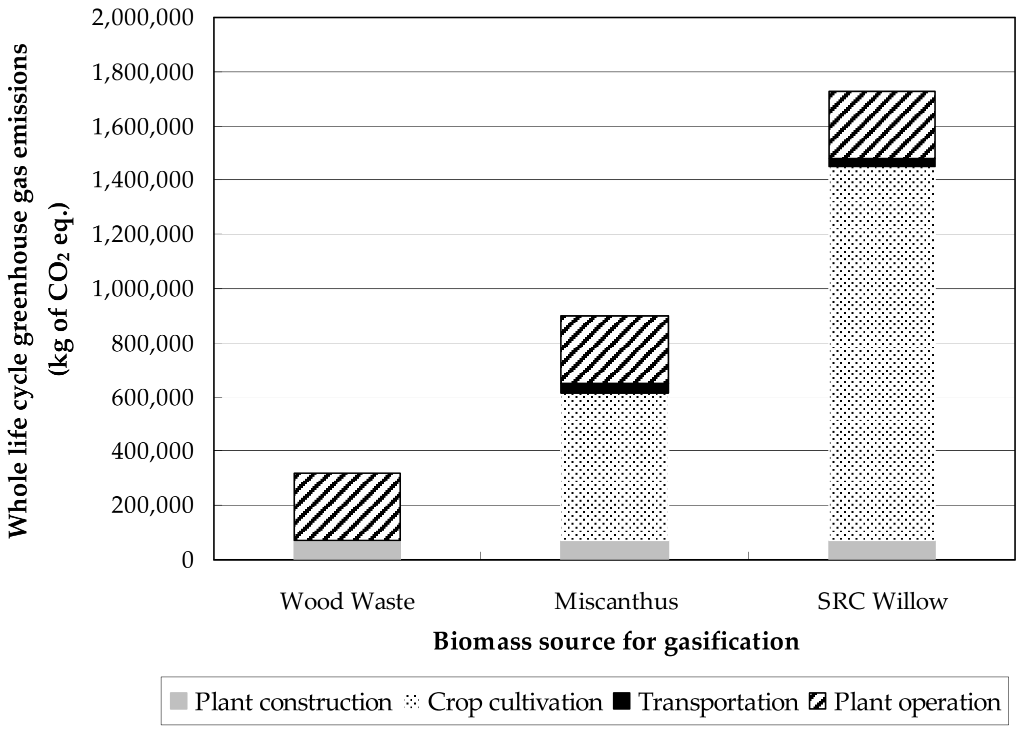


Figure 10-1: Whole life cycle greenhouse gas (GHG) emissions for the biomass gasification system using different feedstocks

Figure 10-1 shows the biggest contribution to greenhouse gas (GHG) emissions arises from crop cultivation. In contrast transportation does not have a notable impact on the results. When compared to using wood waste the full bioenergy supply chain increases the GHG emissions nearly 3-fold for Miscanthus and more than 5-fold for SRC Willow. Differences between the two crops are primarily explained by the assumptions regarding fertiliser inputs, but also the higher yields obtained from Miscanthus. The relative impact of plant operation would increase if further pre-processing of the biomass is required, i.e. further chipping to a suitable size or drying of feedstock. Similarly the relative impact of transportation will increase with longer transportation distances. In larger scale systems the GHG emissions from transportation will therefore be more significant.

ReCiPe does not account for biogenic emissions, as previously described, hence the results displayed in Figure 10-1 do not show the carbon sequestered in crop growth or greenhouse gas emissions from producer gas combustion. It is however useful to portray this carbon flow. Guinee (2009) suggests CO_2 should be counted explicitly for in biomass production. A description of how to calculate CO_2 fixation in biomass was included in Chapter 6, which if applied to crop growth does produce negative GHG emissions up to the farm gate. When the biomass goes through the gasification process and subsequent combustion the net effect is carbon neutral (see Figure 10-2). Note that for wood waste it is debatable whether the carbon sequestered should be accounted for as the production of wood waste was outside the system boundary, as indicated by the black dotted line in Figure 10-2.

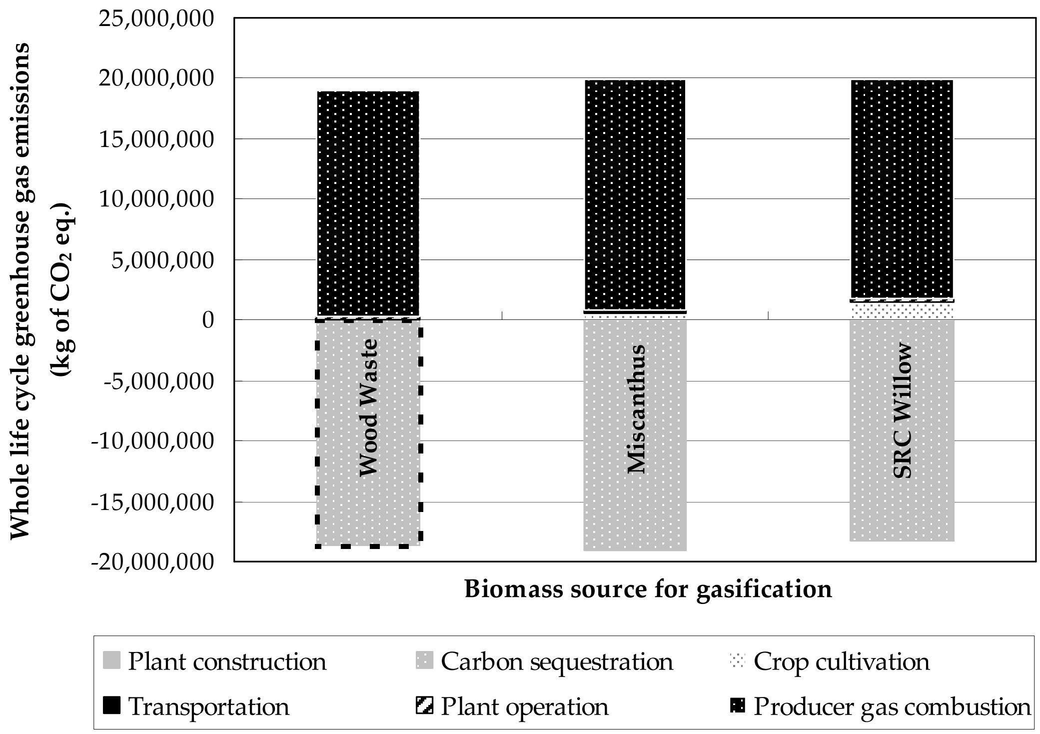


Figure 10-2: Effect of including biogenic carbon emissions on whole life cycle greenhouse gas (GHG) emissions

In Chapter 6 it was noted that soil carbon balances were not included in the LCA due to their site-specific variability. Many factors can influence soil carbon dynamics in bioenergy systems (IEA, 2006). There are however potential carbon storage pools in the Miscanthus or Willow coppice systems that deserve attention. A detailed assessment of this is beyond the scope of this thesis. However a discussion is included here to provide some background to soil carbon in perennial energy crops.

Soil contains large amounts of carbon, primarily in association with its organic content. Carbon, as it relates to the organic matter of soils, is a major component of soil and catchment health (Harrison, 1999). Several factors affect the variation that exists in soil organic matter (SOM) and soil organic carbon (SOC), the most significant being the influence of humans and agricultural systems (Rowe *et al*., 2009).

In Britain, arable soils usually contain fairly low amounts of carbon, 5-60t C/ha, depending on the soil type and management, while for forestland the value is estimated to be between 50-350t C/ha

(Matthews, 2001). For soils in short rotation coppice cultivation the amount of carbon in soil is somewhere between those for arable soils and forestland, e.g. from 40-200t C/ha (Matthews, 2001). Accordingly, as a result of planting arable land with coppice, the soil carbon storage is expected to increase, while a reduction could be observed when forest or grassland is replaced.

A review of recent studies showed that in terms of changes in SOC, excluding any sequestration in living biomass (SOM), the potential for carbon sequestration in SRC Willow within the UK is good (Rowe *et al.*, 2009). Increases in SOC could contribute around five per cent of the carbon mitigation benefits of this crop (Grigal & Berguson, 1998). Other studies provide varied findings (Borjesson, 1999; Grogan & Matthews, 2002; Makeschin, 1994). It is illustrated that how the land was used previously needs to be considered when locating SRC plantations (Jug *et al.*, 1999). Miscanthus, like SRC Willow, also shows varied results of the effect on SOC (Kahle *et al.*, 2001; Hansen *et al.*, 2004).

From the above studies, it can be seen that varied results for SOC sequestration are attributable to a number of factors. These include: annual precipitation, soil texture, climate and initial soil carbon content (Grigal & Berguson, 1998; Grogan & Matthews, 2002; Hansen *et al.*, 2004). Despite these variations there is a general consensus that the conversion of arable land to SRC Willow or Miscanthus will result in an increase in carbon sequestration, while the conversion of grassland may not be as beneficial (Rowe *et al.*, 2009). This view was echoed by King *et al.* (2004), who suggest that while conversion of arable land to SRC Willow or Miscanthus will result in increase in SOC of 0.55–0.83t C/ha/yr per hectare per year and 0.49–0.73t C/ha/yr respectively, conversion of grassland to either of these crops cannot be expected to increase SOC.

10.1.2 Human toxicity

Human toxicity in the BGP using wood waste comprises of emissions such as Mercury, Lead and Arsenic released to air; Zinc and Lead released to soil; and Arsenic, Selenium and Lead released to water. These emissions arise primarily from plant construction, ash disposal, waste wood, and UK grid electricity use. Emissions of 1,4-DBeq. for crop cultivation and the BGP are again taken from Chapters 6 and 8 respectively. Transportation emissions are assumed to be 9.9g 1,4-DBeq. per tonne-km (see Appendix I). Results displayed in Figure 10-3 combine these findings and show the human toxicity emissions for the whole life cycle based on the assumptions outlined in Chapters 6 to 9.

Including crop growth and transportation in the full life cycle increases the human toxicity emissions by over 50% for Miscanthus and over 100% for SRC Willow. This is almost entirely due to upstream emissions associated with crop cultivation. The production of inorganic fertilisers and herbicides was found to release Vanadium, Mercury, Lead, Arsenic, Cadmium, and Barium. Most notable is the production of ammonia and nitric acid in producing Nitrogen fertiliser. The production of chemical plants also contributes towards the impacts associated with inorganic chemical production. The construction of the storage barn for storing perennial energy crops was also found to release Mercury, Lead, Arsenic and Manganese from steel and concrete manufacture.

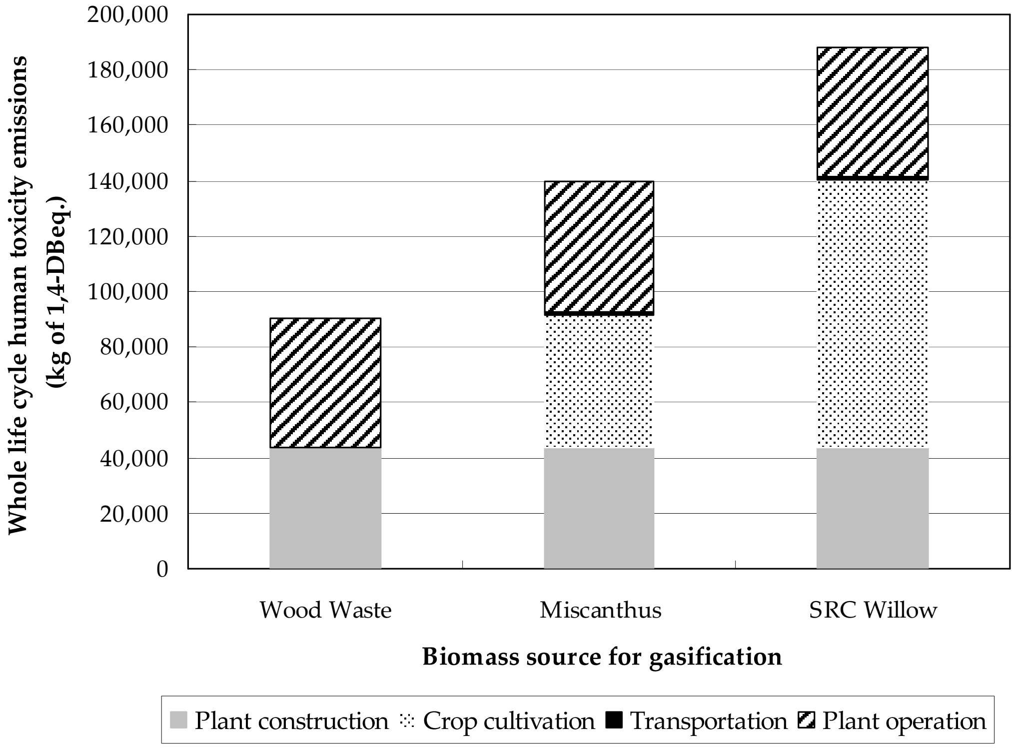


Figure 10-3: Whole life cycle human toxicity emissions for the biomass gasification system using different feedstocks

10.1.3 Terrestrial ecotoxicity

Almost all of the impacts for terrestrial ecotoxicity were found to arise from the biomass gasification plant operation. Phosphorous contained in the ash contributes to almost 100% of this impact category, as described in Chapter 8. Crop cultivation and transportation were found to make less than 0.1% contribution to the impact category. It should be noted that the composition of Miscanthus or Willow ash may not contain phosphorous, as assessed in the sensitivity analysis in Chapter 8. However there was only one sample of Willow ash and so the results are somewhat inconclusive. It is also possible that ash produced from plant operation is inert and therefore does not have an impact. Nonetheless, it can be concluded that terrestrial ecotoxicity is not greatly affected by the system expansion, and that its key determinant is the composition of ash.

10.1.4 Particulate matter formation

Particulate matter formation was found to arise at all stages of the life cycle, representing potential damages to human health through the respiratory system. The LCI data for NO_x and particulate emissions from the BGP operation was inconclusive, as described in Chapter 8. To take a conservative approach it was decided to take UK emission limits for the emissions from producer gas combustion (sensitivity case T). This assumes the worst case scenario, but in reality the emissions may be much lower than this. Emissions for crop cultivation were taken from Chapter 6 and transportation was assumed to release 0.64g per PM10eq. per tonne-km (see Appendix I). Results displayed in Figure 10-4 combine these findings and show the particulate emissions for the whole life cycle based on the assumptions outlined in Chapters 6 to 9.

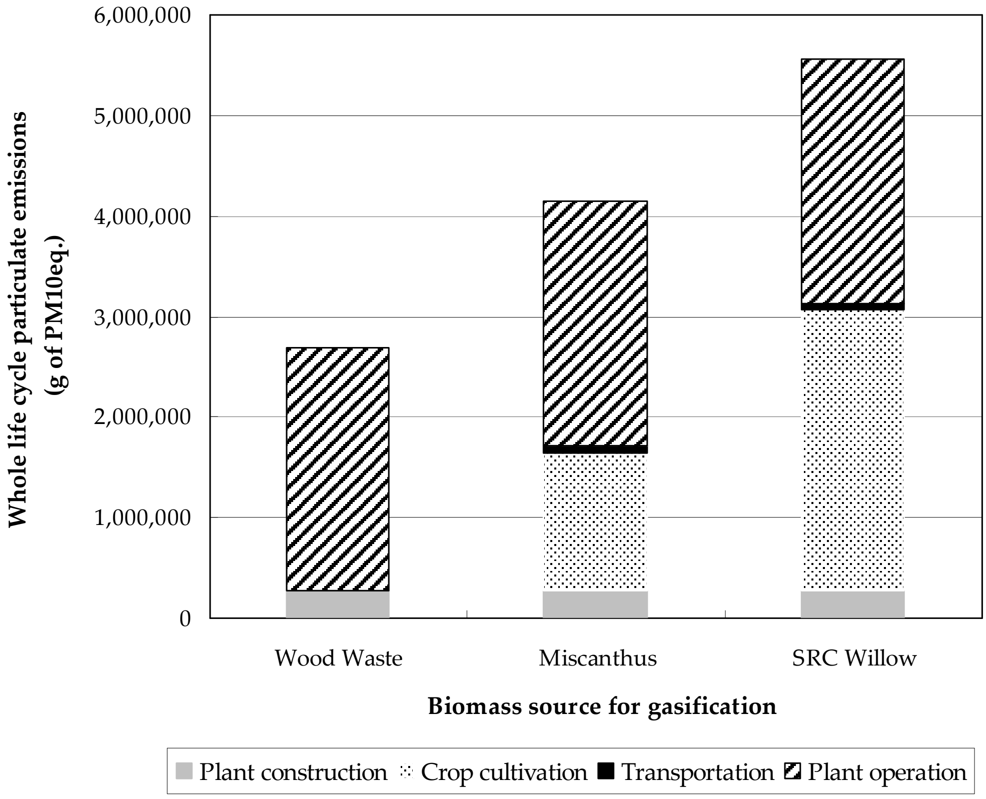


Figure 10-4: Whole life cycle particulate emissions for the biomass gasification system using different feedstocks

Crop cultivation makes an important contribution to the amount of particulate emissions from the full life cycle. Ammonia and Nitrogen oxides emissions arise primarily from the use of Nitrogen fertiliser. Diesel used by the tractor in field operations also releases emissions of Ammonia, Nitrogen oxides, Sulfur dioxide and particulates. Transport emissions also arise from the combustion of diesel but are not significant due to the relatively low amount of feedstock to be transported and the short distances travelled. Overall, emissions from the plant operation are the most important when the UK emission limit values are taken.

10.1.5 Agricultural land occupation and transformation

There is negligible agricultural land occupation associated with transportation and plant operation, so it becomes obvious that the cultivation of perennial energy crops makes a critical contribution to this impact category. Biomass gasification using wood waste in comparison has a much more limited amount of agricultural land use. Miscanthus will potentially use up less land in the South West region compared to SRC Willow due to the higher assumed yields obtainable (DEFRA, 2007d). Further analysis will focus on a qualitative assessment of agricultural land occupation and transformation due to the uncertainties associated with trying to quantify this impact category.

Land used for biomass growth will often compete with food crops, forest and urbanisation. However in some situations biomass cultivation can be used to rehabilitate degraded or marginal soil (IEA, 2006). Transformation of land will affect the environmental cost or benefit of bioenergy systems. Where land with high species diversity is bought over to a monoculture, then this causes damage to ecosystems and natural capital (Haines-Young, 2009). When existing arable land is transformed to perennial crop use or if degraded or marginal land is used, this may have benefits for biodiversity and soil carbon. Conversely, land occupation is an issue as it prevents land returning to its natural state. Agricultural land occupation therefore represents a key driver of the loss of biodiversity and ecosystem services (Haines-Young, 2009).

The most productive land is agricultural pasture, otherwise used to produce food. In areas where soils are less ideal, crop yields are lower, sometimes to the point where the energy gain ratio is too low to be economical. Abbasi & Abbasi (2010) found that forest products have a higher economic value per MJ in their original form than when converted to heat or gaseous energy. The allocation of valuable agricultural land and the destruction of natural forestry for energy crops can therefore be considered unsustainable (Evans *et al.*, 2010).

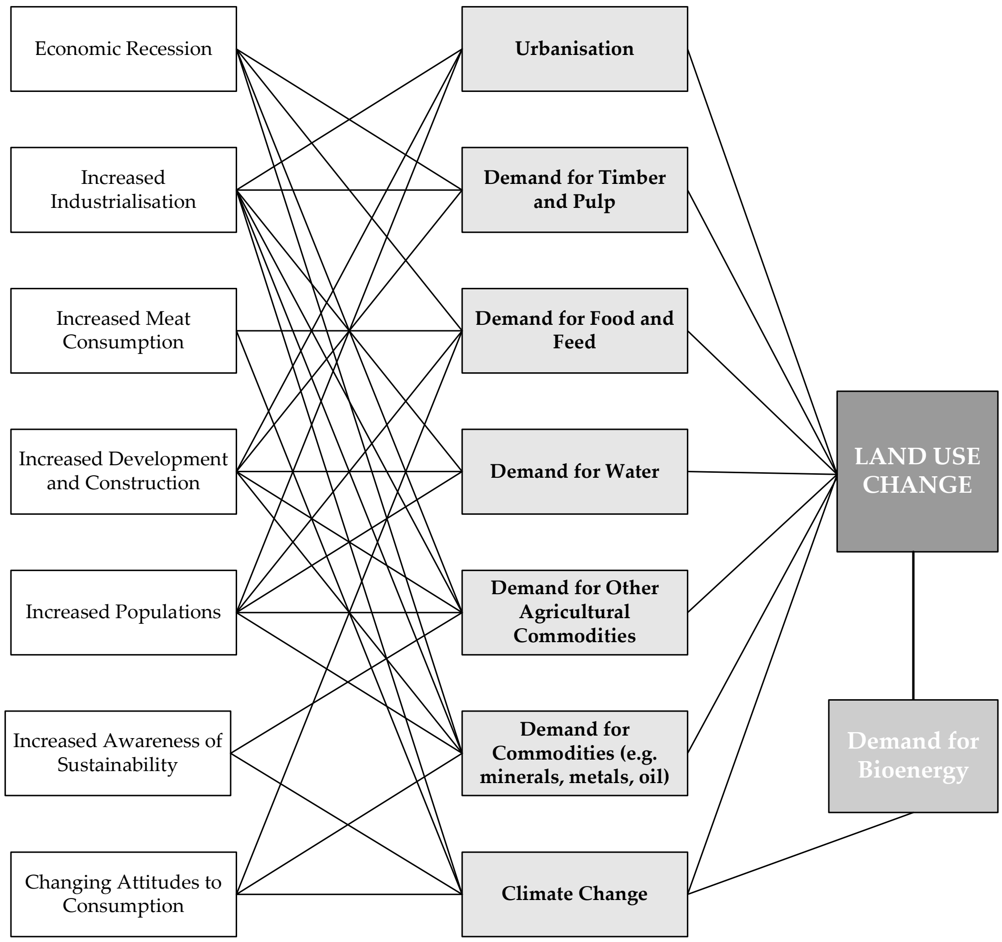


Figure 10-5: Drivers for land use change – adapted from the Gallagher Review (RFA, 2008)

Figure 10-5 demonstrates the complex web of interacting demands which affect land use, even before bioenergy is considered (RFA, 2008). This is not an exhaustive list but shows the wide variety of factors which drive land-use change.

Individual farmers will be affected by a range of elements which includes their own skills, knowledge, resources, time and confidence. In addition, their decisions are also based on macro drivers supplied by business and Government, such as finance, markets, transport, storage, contractors and advice. The wider environment, such as climate change, water quality, drought, disease, community expectations and so on, will also impact on land use decisions. Table 10-1 attempts to highlight some of the main factors which affect farmers' decisions on land use.

Table 10-1: Factors which affect farmers' decisions on land use

Farmer business decisions	Growing profitable crops; Diversifying and entering new markets; 'Cash cows' – stable income; Risk versus reward; Contracts with developers or businesses; Grants and subsidies available.
Environmental decisions	Impact on land, soil, water resources, etc.; Agri-environmental schemes; Biodiversity impacts; Climate – suitability of crops; Yields.
Personal motivation	Experience; Habit/tradition; Family decision – education, enjoyment, learning farming skills; Age of farmer – retirement, next generation.
Resource availability	Sufficient and suitable land; Capital equipment requirements; Expertise of farmer – need for contractors; Skilled workers; Cropping methods and use of agro-chemicals.

Smeets *et al.* (2007) reviewed a number of studies which indicated that between 15% and 72% of the global land area used for food crops (using a base year of 1998) could be made available for energy crops in 2050 without significant consequences on food prices. However the world food demand combined with increased land competition for bioenergy is still a key concern for many governments (FAO, 2008). Society therefore has to make choices as to the best (or most appropriate) usage of land. As large amounts of land in the UK and abroad are in private ownership, and with an ever growing global population, it is clear that land occupation and transformation for bioenergy will remain a complex issue for the foreseeable future.

10.1.6 Metal depletion

The depletion of metal resources in the BGP was shown in Chapter 8 to be caused primarily through the plant construction. When the cultivation of crops is considered it is mainly the use of agricultural machinery, with small contributions from the production of agro-chemicals. Metal depletion for transportation is assumed to be 10.1g of Fe eq. per tonne-km (see Appendix I). Results displayed in Figure 10-6 combine these findings and show metal depletion for the whole life cycle based on the assumptions outlined in Chapters 6 to 9.

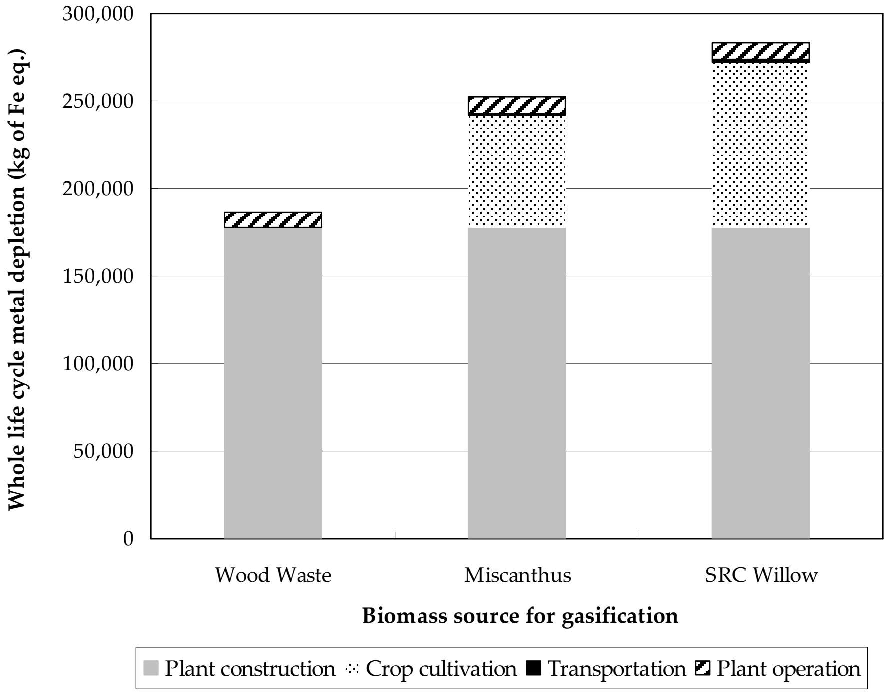


Figure 10-6: Whole life cycle metal depletion for the biomass gasification system using different feedstocks

Figure 10-6 confirms that it is the plant construction which is the main life cycle stage contributing towards metal depletion. Crop cultivation does increase the overall impact by up to 50% due to allocation of farm machinery, the manufacture of agro-chemicals and the construction of storage facilities for the feedstock. The impacts of transportation and plant operation on metal depletion were found to be negligible.

10.1.7 Fossil fuel depletion

Fossil fuel depletion was found to be the most important impact category in the LCA of the cultivation of crops and the plant construction and operation. Net energy analysis results also showed that the gross energy requirement (GER) for bioenergy systems is dominated by fossil fuel use. When the transportation of biomass is considered it is also seen as crucial, consuming 105g of oil eq. per tonne-km (see Appendix I). Results displayed in Figure 10-7 combine these findings and show fossil fuel resource depletion for whole life cycle based on the assumptions outlined in Chapters 6 to 9.

When compared to using wood waste the full bioenergy supply chain increases fossil fuel depletion by more than 2-fold for Miscanthus and 4-fold for SRC Willow. Fossil fuel depletion follows similar findings to climate change since crop cultivation makes the biggest contribution and transportation is less important. Further analysis of this is not warranted here due to the overlap with the net energy analysis performed in Chapter 9.

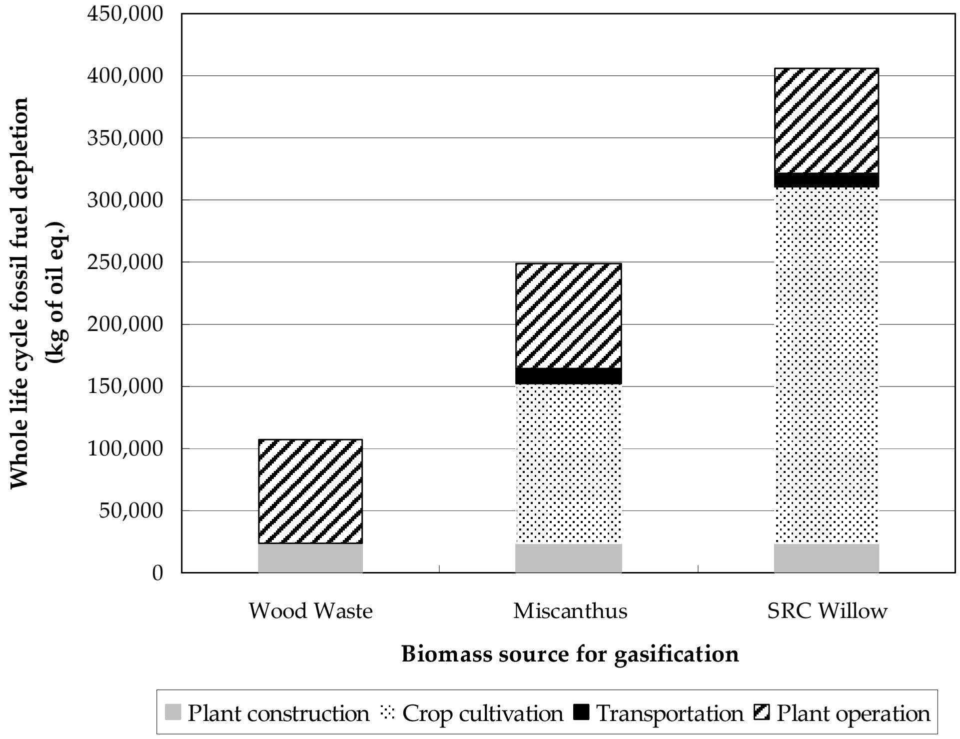


Figure 10-7: Whole life cycle fossil fuel depletion for the biomass gasification system using different feedstocks

10.1.8 Acidification and Eutrophication

Acidification and eutrophication were potential issues with crop cultivation, but less so with transportation and plant operation. Phosphates from agricultural land to ground and surface waters can be a significant problem in intensive farmland areas. Measures to prevent leaching of nutrients include reducing inputs of fertilisers, widening crop rotations and better farm management. It should however be noted that the release of nitrogen oxides (NO_x) does contribute towards acidification, so these emissions must be minimised at all life cycle stages.

10.1.9 Water Depletion

Water depletion is a difficult impact category to conclude upon. The operation of the plant directly uses 60 litres per hour through gas cleaning, which is supplied via the local water supply company. There are also indirect uses of water, such as through various industrial processes in the supply of UK grid electricity. In contrast perennial energy crop production is reliant on natural rain water rather than the water supply system. Agricultural water use is a serious concern especially in southern parts of Europe, where water availability is low and varies from year to year. Increases in irrigated land have contributed to water scarcity, with the lowering of water tables and water levels in rivers and lakes (EEA, 2006). Water depletion is not currently given much attention in the UK when compared to other issues such as climate change. However, the use of LCA is crucial in providing information on the water consumption of different industrial systems.

10.2 POTENTIAL LIFE CYCLE ENVIRONMENTAL IMPACTS OF DIFFERENT ENERGY SYSTEMS

LCA results from this thesis are compared to other LCA studies in order to verify and critique the present study. It is beyond the scope of this thesis to compare all of the LCIA results with all other energy systems. Nonetheless it is valuable to put the results in the context of some different energy systems. Where published results were available for comparison, a selection are presented here.

10.2.1 Climate change

Alongside net energy analysis, by far the most numerous studies have assessed the greenhouse gas (GHG) emissions associated with different energy systems. Firstly a review of previous studies relating to GHG emissions from perennial crop growth was performed. The findings for perennial energy crops are summarised in Table 10-2.

Table 10-2: Greenhouse gas emissions for Miscanthus and SRC Willow – review of previous studies

Author(s)	Country / Region	GHG Emissions $gCO_2eq./kg$	Comments
Miscanthus			
Bullard & Metcalfe, 2001	UK	9.1	Accounts for carbon only; widely cited in UK literature
Styles & Jones, 2007	Ireland	265.3	Very high fertiliser input assumed; other inputs are similar to the present study although upstream inventory not as detailed.
Smeets *et al*, 2009	Europe	69-86	Assumes an annual fertiliser input; other inputs are similar to the present study.
This thesis (2011)	**UK**	**51.1**	
SRC Willow			
Lundborg, 1997 (cited in Boman & Turnbull)	Sweden	24.9	Accounts for carbon only; unable to obtain supporting data.
Dubuisson & Sintzoff, 1998	Belgium	31.1	Accounts for carbon only; not very tranparent inventory (upstream processes, etc.); does not account for CO_2 sequestration; Belgium Agronomic Practices; does not account for farm machinery.
Matthews, 2001	UK	23.8	Widely cited in UK literature; low fertiliser input; assumed yields are very high; not very detailed upstream inventory.
Elsayed *et al*, 2003	UK	32.0	Widely cited in UK literature; does not include any inputs for fertilisers; assumed yields are not stated.
Heller *et al*, 2003	USA	12.4	Less detailed inventory (upstream processes, etc.); accounts for CO_2 sequestration; US Agronomic Practices; does not account for farm
Styles & Jones, 2007	Ireland	184.3	Very high fertiliser input assumed; other inputs are similar to the present study although upstream inventory not as detailed.
Goglio & Owende, 2009	Ireland/ Italy	41.0	Based on previous LCA studies; not very detailed inventory; does not account for farm machinery or CO_2 sequestration.
This thesis (2011)	**UK**	**137.6**	

Table 10-2 reveals that results vary widely depending on the system boundary and assumptions used. Nonetheless the results from this thesis are thought to be a realistic scenario as the inventory used is generally more detailed than previous studies due to wider system boundaries. Other differences in findings can be explained through the assumptions made in each study.

In another study, St. Clair *et al.* (2008) estimated the pre-harvest GHG emissions of energy crop production. They assessed pre-harvest GHG costs of production of SRC Willow, Miscanthus and oilseed rape (OSR) when compared to a range of former land use baselines. It was found that GHG costs are very low for Miscanthus and SRC Willow but higher for OSR production, determined mainly by the need for nitrogen fertilisation (St. Clair *et al.*, 2008). Compared to baseline land uses, SRC Willow and Miscanthus have much lower GHG costs than arable cropping or intensively managed grasslands, with OSR production having similar GHG costs to arable cropping. Establishing broadleaved forests has low GHG costs, but five-year GHG costs of Miscanthus and SRC Willow are similar to forest (St. Clair *et al.*, 2008). Former land use is also of critical importance when determining if energy crops are a net source or sink of GHGs. Converting to SRC Willow and Miscanthus are the most favourable energy crops in terms of GHG savings (St. Clair *et al.*, 2008).

Results for other LCA studies of similar bioenergy pathways show that the results for biomass gasification calculated in this thesis are comparable (see Table 10-3). As previously discussed the main variances are attributable to a number of factors including the technology, individual study assumptions, system boundaries, etc.

Table 10-3: Greenhouse gas emissions for selected bioenergy pathways – review of previous studies

Author(s)	Country / Region	GHG Emissions gCO2eq./MJ	End use / technology / comments
Miscanthus			
Elsayed *et al* ., 2003	UK	26.0	Electricity - Combustion
Styles & Jones, 2007	Ireland	36.4	Electricity - Combustion
This thesis (2011)	**UK**	**17.2**	**Electricity only - Gasification**
	UK	**8.7**	**CHP (50% heat) - Gasification**
SRC Willow			
Elsayed *et al., 2003*	UK	5.0	CHP - Gasification
		7.0	Electricity - Gasification
		15.0	Electricity - Pyrolysis
		23.0	Electricity - Combustion
Koelin & Volk, 2005	USA	10.8	Electricity - Gasification (NREL gasifier)
		11.2	Electricity - Gasification (EPRI gasifier)
		14.5	Electricity - Combustion (EPRI direct-fired)
Styles & Jones, 2007	Ireland	36.7	Electricity - Combustion
Goglio & Owende, 2009	Ireland/ Italy	134.0	Electricity - Gasification
This thesis (2011)	**UK**	**37.2**	**Electricity only - Gasification**
	UK	**18.8**	**CHP (50% heat) - Gasification**
Wood			
Mann & Spath, 1997	USA	254.4	Electricity - Gasification of wood (energy crops)
Carpentieri *et al* ., 2005	Italy	-165.0	Electricity - Gasification of wood (energy crops) with CO_2 removal
Elsayed *et al* ., 2003	UK	8.00	CHP - Combustion of wood chip (forestry residues)
		7.00	Heat - Combustion of wood
This thesis (2011)	**UK**	**6.0**	**Electricity only - Gasification of waste wood**
	UK	**3.0**	**CHP (50% heat) - Gasification of waste wood**

As a final comparison the GHG emissions for different electricity systems from previous studies have been reviewed. This is not an exhaustive review but aims to give some further context as to how the bioenergy systems assessed in this thesis compare to other forms of electricity generation (see Table 10-4).

Table 10-4: Greenhouse gas emissions for selected electricity systems – review of previous studies

Author (s)	Technology	GHG Emissions gCO2eq./MJ	Capacity/configuration/fuel
Pehnt, 2006	Wind	2.5	2.5 MW, offshore
	Hydroelectric	2.8	3.1 MW, reservoir
	Wind	2.8	1.5 MW, onshore
	Biogas	3.1	Anaerobic digestion
	Hydroelectric	3.6	300 kW, run-of-river
	Solar thermal	3.6	80 MW, parabolic trough
	Biomass	3.9	Forest wood Co-combustion with hard coal
	Biomass	6.1	Forest wood steam turbine
	Biomass	6.4	Short rotation forestry Co-combustion with hard coal
	Biomass	7.5	Forest wood reciprocating engine
	Biomass	8.6	Waste wood steam turbine
Fthenakis *et al* ., 2008	Solar PV	8.9	Polycrystalline silicone
Pehnt, 2006	Biomass	9.7	Short rotation forestry steam turbine
	Geothermal	10.6	80 MW, hot dry rock
	Biomass	11.4	Short rotation forestry reciprocating engine
Sovacool, 2008	Nuclear	18.3	Various reactor types
Gagnon *et al, 2002*	Natural gas	123.1	Various combined cycle turbines
	Fuel cell	184.4	Hydrogen from gas reforming
	Diesel	216.1	Various generator and turbine types
	Heavy oil	216.1	Various generator and turbine types
	Coal	266.7	Various generator types with scrubbing
	Coal	291.7	Various generator types without scrubbing

10.2.2 Fossil fuel depletion

A comparison of biomass gasification with other energy systems shows that fossil fuel depletion is more of an issue than low carbon technologies such as wind and solar power (Allen, 2009). Conversely when compared to the main electrical generation systems, with the exception of nuclear energy, biomass gasification causes less fossil fuel depletion. Some data from Ecoinvent was used to calculate fossil fuel depletion for the main large scale electrical systems (see Figure 10-8).

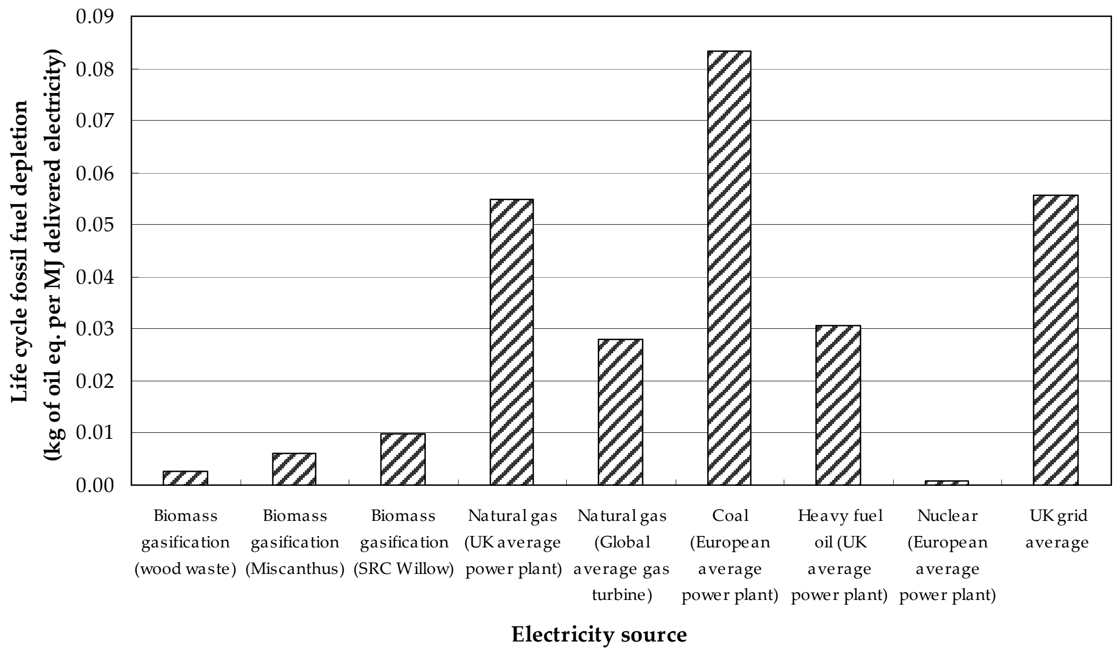


Figure 10-8: Fossil fuel depletion for selected electricity systems (calculated using data from DECC, 2009a; Goedkoop *et al.*, 2009; Swiss Centre for Life Cycle Inventories, 2009)

10.2.3 Other environmental impact categories

A review of other environmental impact categories is difficult due to insufficient results available for detailed comparison. This is because most previous studies of bioenergy systems have focused on net energy and carbon balances. This section therefore provides a brief summary of how other environmental impacts arising from bioenergy systems compare to different energy systems, based on previous studies.

10.2.3.1. Particulate matter formation

Data on particulate emissions from for the same electricity sources as above was obtained from the Ecoinvent database and calculated using ReCiPe midpoint. This showed that coal produces the highest PM_{10} eq. emissions (~399g/GJ_e), whilst nuclear is lowest (~6g/GJ_e). Heavy fuel oil is also quite high (~271g/GJ_e), with the UK Grid lower (~163g/GJ_e) and natural gas lower still (~39g/GJ_e). It is difficult to compare results for biomass gasification due to inconclusive data. However, assuming UK emission limits gives (~59g/GJ_e), which is slightly higher than natural gas. Particulate emissions will also be much higher than other renewable sources, such as wind power, hydro and solar. Valuable recent work has been performed on air emissions from biomass heat and power systems (see for example, Jonsson & Hillring, 2006; Thornley, 2008)

10.2.3.2. Land Use

Land use is the environmental impact category in which bioenergy has a higher impact than most other types of energy system. This is not always the case when waste is used as a feedstock, but waste and residue biomass sources still require land to be cultivated initially. Fthenakis & Kim (2008) compared land transformation and occupation across a range of electricity systems. They found that solar photovoltaic (PV) requires the least amount of land among renewable energy options, while the biomass cycle requires the largest amount. In terms of land occupation biomass cycles requires the greatest amount, followed by the nuclear fuel cycle. This was also calculated using data from the Ecoinvent database and using ReCiPe midpoint, which confirmed that bioenergy systems generally use more land than any other energy systems.

10.3 ENVIRONMENTAL IMPACT CATEGORIES NOT COVERED BY LCA

Some environmental impact categories potentially relevant to bioenergy systems are not covered by LCA. Therefore a brief discussion of these is provided here. Odour is not considered to be a concern for biomass gasification or perennial crop growth, but could be in other bioenergy systems where wastes and residues are used. Noise is a potential issue at times of harvest for perennial crop growth, and near to the BGP during operation. Soil erosion is a possible issue with farming although previous studies suggest perennial crop growth may reduce soil erosion when compared to annual crops (Rowe *et al*., 2009; Smeets *et al.*, 2009). It is however biodiversity which warrants the most consideration in bioenergy systems due to the amount land required. Several studies show that the biodiversity in Miscanthus and SRC Willow fields is generally higher compared to conventional annual crops (Sage, 1998; Sage *et al*., 2006; Semere & Slater, 2007; Smeets *et al.*, 2009). A detailed review is not required here as previous studies have completed this (e.g. Rowe *et al*., 2009).

10.4 SUMMARY

This chapter has bought together the results from Chapters 6 to 9 to expand the LCA study to assess the environmental effects of the full bioenergy supply chain. The main finding from this system expansion is that the growth of perennial energy crops makes a significant contribution to the overall life cycle, whereas transportation does not (assuming relatively localised production). The use of dedicated energy crops for biomass gasification therefore greatly increases the potential impacts for this bioenergy system when compared to using waste feedstocks. However there may also be potential advantages of perennial crops in comparison to annual crops, such as increases in soil carbon and improved biodiversity. Thus the choice of type and location of feedstock is critical in determining the potential environmental impacts of bioenergy systems.

A comparison with the results of other LCA studies has shown that biomass gasification has a lower environmental burden for most impact categories when compared to fossil fuel based systems. The main exception to this is land occupation as using energy crops requires significantly more land than other energy systems. When comparing the findings of this study with other published LCA studies it becomes apparent that direct comparison of results is complicated. This is due to the different ways in which results are reported, assumptions made and different system boundaries. For some impact categories, such as toxicity, there appears to be less published data available. This highlights the need for good primary data, sensitivity analysis and clarity of reporting.

CHAPTER 11. DISCUSSION

In this chapter the main findings from the different studies undertaken in this thesis are discussed. The main implications from this research are highlighted and put into the context of other related studies. Discussion points focus on the significance of the results, the data used, methodologies adopted and any potential limitations of the research. This discussion chapter therefore aims to synthesise the work completed in the previous chapters in a coherent manner.

11.1 INTRODUCTION

To put the discussion of this thesis into context, it is first necessary to restate the original research aims. The general aim (described in Chapter 1) was to distinguish the current UK bioenergy situation, understand how this may develop, and assess what the energy potential and possible environmental impacts of an increase in bioenergy production could be. More specific aims were chosen as:

- Identifying the main barriers to and drivers for UK bioenergy development;
- Quantifying the existing available biomass resource in the South West of England;
- Assess the potential environmental impacts of perennial energy crop growth;
- Examine the environmental life cycle of a biomass gasification plant.

This thesis has used several techniques and methodologies to assess UK bioenergy production and use. The initial focus of the work analysed the various barriers to and drivers for UK bioenergy development. This offered a good understanding of the current UK bioenergy situation and considered how this may develop over time. Subsequently a resource assessment for the South West of England region was undertaken. This provided both a quantitative analysis of the available resource in the region, and a clear description of the methodology used to undertake a resource assessment. It showed that the current biomass resource is underutilised for energy production which demonstrates a valuable link with the barriers study, i.e. it is crucial to understand and address the barriers to successful implementation of bioenergy projects in order to maximise bioenergy utilisation.

Findings from the resource assessment indicated that for a large increase in future biomass supply dedicated energy crops would need to be grown on a much wider scale than at present. Hence it was identified that there was a research need to assess the potential life cycle environmental impacts of perennial energy crop production. Previous 'life cycle' studies have also predominantly concentrated on energy and carbon assessments and not other impacts. Consequently a life cycle assessment (LCA) and net energy analysis were completed on the cultivation of Miscanthus and short rotation coppice (SRC) Willow based on growing conditions in the South West of England.

From the initial research it was also identified that gasification offers good potential for biomass conversion to energy. The most promising end-use was considered to be combined heat and power (CHP) as this maximises the energy and exergy potential of the feedstock. It was therefore recognised that undertaking a LCA and net energy analysis of this type of biomass gasification CHP plant provides an original research contribution, as no such previous studies which follow LCA methodology were found in the literature.

11.2 BARRIERS TO AND DRIVERS FOR UK BIOENERGY DEVELOPMENT

A range of barriers and drivers to UK bioenergy development were identified in Chapter 4 through a comprehensive literature and case study review. These were then assessed via an online survey completed by various stakeholders grouped: farmers/suppliers, developers, primary end-users, and Government/policy. The survey questionnaire results show that although the barriers and drivers are different for each stakeholder group there are also some similarities between the groups. Whilst the diversity of bioenergy systems means that care needs to be taken when interpreting these findings, they do give a useful insight into the most important factors affecting the development of bioenergy schemes.

11.2.1 Implications for UK bioenergy development

Several links have been identified between the barriers of different stakeholder groups, and economic ones are common across the whole supply chain. The three most critical barriers for the suppliers of biomass feedstocks all relate to economic considerations. Developers identify development and operational costs, and uncertainty over Government support schemes as very important, in the case of end-users, the biggest barrier is the high buying costs with respect to fossil fuels. Technology barriers are also common across some stakeholder groups. Developers and Government/policy advisors rate the unproven nature of conversion technologies as a critical barrier.

Barriers for developers appear very technology based. The uncertainty and hesitance of bioenergy developers suggests that conversion technologies are often not reliable or profitable. This may change with the development of UK Government incentives: the double ROCs, the feed-in tariffs, and the renewable heat incentive. However, developers also cite feedstock availability as a barrier and so again, mechanisms to link farmers and developers would be beneficial. End users will predominantly buy the cheapest and most reliable fuel, therefore financial support mechanisms are presently required to make bioenergy more competitive.

Reducing carbon emissions and dependency on fossil fuels is the main common thread between the drivers for all stakeholder groups. Clearly net energy and carbon balances for bioenergy projects must be proven in order to meet these concerns. This finding was consistent with Buchholz *et al*. (2009) who found that energy balance and greenhouse gas balance were critical in the sustainability of bioenergy systems. However, suppliers and developers both rate economic drivers as being of critical importance. This is understandable as both groups are commercial 'actors' that rely on profit for survival.

The present research highlights a number of implications for the future of bioenergy in the UK. Of primary importance for all stakeholder groups in the supply chain is the economics of bioenergy systems. In order for bioenergy to be successful the growth of energy crops must be profitable for the farmer in both the short and long term. Competition with food for land is problematic both in terms of food production, but also in terms of public perception of the use of bioenergy. Therefore, mechanisms to promote alternative biomass feedstocks, such as farm wastes, ought to be considered. Developers are only likely to invest in bioenergy if a reasonable financial return can be obtained. Similarly end-users will purchase bioenergy when it is competitive with current fossil fuels based fuels. However, the sustainability of bioenergy is key and care must be taken to ensure that any bioenergy technologies promoted and supported do lead to a reduction in GHG emissions and do not increase other environmental burdens.

11.2.2 Limitations in the adopted methodology

With any questionnaire, there will always be the potential for bias and uncertainty (Hammond & Waldron, 2008). Potential weaknesses in the online survey include the description of each barrier or driver, the way which the questions are worded, the order in which they are numbered, the stakeholder's background or point of view, or the sample size. An attempt was made to address these issues during the design of the questionnaire. For example, the survey allowed each barrier and driver to be rated in importance; a clear description was given for each barrier or driver; and additional barriers and drivers could be added by respondents. However, individual interpretations were clearly beyond the authors' control. The questionnaire was only sent to individuals who were known to have key experience in the bioenergy industry. This could be viewed as a limitation as other stakeholders, such as the public, were not included in the study. It is acknowledged that public perception and acceptability of bioenergy schemes is crucial, but the scope of this work was limited to those stakeholders integral to the supply chain.

Another potential limitation of this research is that the survey assessed bioenergy as a whole, rather than individual bioenergy pathways. However, this could also be interpreted as an advantage since the study incorporates a range of feedstocks and technologies, and provides some useful results for policy makers. Nevertheless it is acknowledged that the barriers to individual bioenergy pathways could be different and therefore future work should concentrate on assessing the barriers for different biomass sources and technologies.

11.3 BIOMASS RESOURCE ASSESSMENT FOR THE SOUTH WEST OF ENGLAND

A biomass resource assessment was undertaken for the South West of England in Chapter 5. This region was chosen due to the research interests of the Great Western Research alliance (GWR), as described in Chapter 1 section 5. The methodology used could however be easily applied to other regions of the UK. The resource assessment defined each feedstock, reviewed existing resource estimates, collected data on resource availability, analysed this data and calculated the available resource. Different constraints on accessing the available resource were reviewed before quantifying the total resource and defining a resource equation for each feedstock.

11.3.1 Implications of the resource assessment results

This study demonstrated that there are a wide variety of biomass feedstocks available in the South West, and throughout the UK. A total of 16-20PJ_{NCV} of biomass resources was calculated to be currently available in the South West region. This total is lower than previous resource assessments: ~81PJ_{NCV} (Scholes, 1998); >200PJ_{NCV} (Capener *et al.*, 2005); 28-49PJ_{NCV} (Hammond *et al.*, 2008), but has taken a more conservative approach in terms of sustainability and availability. The Hammond *et al.* (2008b) study also demonstrates the diversity of biomass resources available in the region, with the main difference in total explained by the assumptions regarding availability, accessibility and competing uses. The Scholes (1998) and Capener *et al.* (2005) studies focus on the future potential for Miscanthus and SRC Willow, which are not considered to be realistic estimates. Differences in results between studies highlight the wide number of assumptions, calculations and data required to estimate available biomass resources.

Due to the region's large agricultural sector animal wastes and residues are readily available and represent a substantial resource. It was estimated that approximately $7PJ_{NCV}$ of animal manures and slurries are presently available in the region. In a previous resource assessment Hammond *et al.* (2008) estimated that cattle waste represented about $4PJ_{NCV}$, however this assumes that only 20% of the resource could be collected. Hammond *et al.* (2008) also found that pig and poultry waste made a much smaller contribution (~$0.4PJ_{NCV}$) which is a similar finding to the present resource assessment. As the South West region's geography favours livestock farming, animal wastes and residues are considered to remain an available biomass resource into the future.

Straw is not considered to be a presently available biomass source for energy use. Straw has too many competing uses, in particular for use as livestock feed, animal bedding, fertiliser and soil structure improver (ADAS, 2008). This result was consistent with ADAS (2008) but is different to Hammond *et al.* (2008) who estimated an available straw resource of $6PJ_{NCV}$. Edwards & Suri (2007) also suggest a reasonable supply of straw available in the UK. However, as the majority of agricultural land in the South West is used for livestock farming and cropping land is quite dispersed, the present study assumes straw is more suited to regions such as the East Midlands and East Anglia where there is an excess straw supply (CSL, 2008). The South West region is a net importer of straw for agricultural purposes. Hence it is not considered to be economic or environmentally sustainable to transport in straw from outside of the region for bioenergy use.

Conventional crops were excluded from the resource assessment due to concerns over competition for land. Using annual food crops for bioenergy use is not considered to be an efficient use of land and raises questions surrounding the fuel versus food debate. Tampier *et al.* (2004) show that crops such as wheat and maize, require high applications of fertiliser, take up prime agricultural land and give low crop yields, making them unsuitable energy crops. However, certain crops such as wheat and oilseed rape are useful in providing feedstocks for certain end-uses, i.e. bio-ethanol and bio-diesel which can be applied to transport fuels.

For biomass to play a significant role in the world's energy future, dedicated energy crops are essential (Evans *et al*., 2010). There is however currently a low uptake of perennial energy crops in both the South West and the UK as a whole. In this study it was established that just under $0.3PJ_{NCV}$ of Miscanthus and SRC Willow are currently available in the South West. Despite the current low uptake several studies do suggest a significant increase is possible in perennial crop growth whilst still pursuing sustainable agricultural practices (EEA, 2006; EEA, 2007; Hammond *et al*., 2008b; ADAS, 2008). Using unutilised agricultural land represents a potential option for perennial energy crop growth. Increases in the total farmed area and set aside are just two of the reasons this may be possible.

Forestry derived biomass sources including forestry residues (~$1.5PJ_{NCV}$), sawmill co-products (~$0.5PJ_{NCV}$), and arboricultural arisings (~$0.5PJ_{NCV}$) are all currently available biomass resources. The total woodfuel resource calculated was similar to two previous studies which identified ~200,000odt (~$3.5PJ_{NCV}$) to be available annually in the South West (Forestry Commission 2005; Forestry Commission, 2007). However this total was lower than that found by Hammond *et al*. (2008) which is a reflection of the higher amounts considered to be collectable in their study. In the present study high sustainability constraints were applied which perhaps explain the lower total found to be available. It is not transparent exactly how the forestry resource was calculated in the Hammond *et al.* (2008) study therefore further comparison is not possible. Nonetheless all studies conclude these resources are available for bioenergy production; the only possible exception is stemwood which is not thought to be available in the present study due to its higher economic value for competing uses. Forests take time to establish and therefore this resource will continue to be available at similar levels in future years.

Waste wood was shown to arise from a variety of industrial sectors indicating that the amount available for bioenergy is likely to vary depending on competing demands and recycling rates. It is therefore difficult to estimate exactly how much is available at any one time. However it was found that ~2.5PJ_{NCV} are currently available which is in line with industry and Governmental estimates (AEA, 2009a, Confor 2010), hence waste wood represents a valuable resource for bioenergy.

Sewage sludge and landfill gas are considered to be close to their maximum potential and represent the largest biomass sources currently used for bioenergy production in the South West. For example, Wessex Water, the largest water company in the South West region have already invested significantly in sewage gas installations (Wessex Water, 2010). Further investment is currently considered unlikely due to better locations already being exploited and the prohibitive capital costs associated with further installations (D. Green, Sustainability planning manager, Wessex Water, 2011, personal communication).

Municipal solid waste (MSW) and commercial and industrial (C&I) waste streams represent a substantial potential resource but is often difficult to collect. This resource is likely to decrease over time due to increased recycling rates and increased regulations on landfill sites. Conversely due to the higher costs associated with waste disposal, using waste for energy generation is becoming more economically attractive. It is therefore likely that in the future more waste will be used for AD and other energy from waste plants.

A final aspect to consider is how the biomass available may change over time. Biomass sources are affected by a range of factors which range from global commodity and fossil fuel prices through to local weather conditions and climate. It is therefore difficult to predict how the availability of biomass will develop based on such factors. Global market prices will directly affect the economic viability of utilising biomass sources for bioenergy production. High food crop prices means that farmers are more reluctant to invest in energy crop production; this combined with fossil fuel prices being low (in comparison to biomass derived fuels) has resulted in a slow uptake of bioenergy. In the future this may not always be the case. The uptake of energy crop cultivation is likely to increase as fossil fuels become more expensive and bioenergy production becomes economically attractive.

Quantifying the biomass resource for a given region is a complex task. This study has shown that due to the diverse range of biomass available, a variety of data collection methods and analyses are required. Whilst this study does not claim to have an exact quantification of all biomass resources in the South West, the methodology applied gives a useful indication of the available resource. By outlining the methods and resource equations for each type of biomass a useful toolkit has been provided. This methodology therefore provides a sound framework with which to apply future resource assessments.

11.3.2 Limitations in the resource assessment

As biomass is such a diverse and dispersed resource an exact calculation of the total amount available is not possible. Instead different estimates and assumptions are made based on a snap shot in time. One limitation of any resource assessment is thus the lack of comprehensive data available required to accurately calculate biomass availability for a given time period. As reliance is placed on several data sources it is very difficult to ensure that each dataset is compiled at the same time. Similarly the variety of data sources means there will always be a margin for error due to statistical discrepancies and different data collection methods and boundaries being employed. Thus it is recommended that one data set which oversees a range of biomass feedstocks could be created and maintained.

Another limitation arises from the qualitative nature of assessing accessibility, availability, competing uses, etc. Various market forces will impact upon biomass supply, which constantly change depending on world market prices, weather patterns and competition. Many biomass sources, like forestry, arise from very competitive markets with several competing uses. Other sources, such as wastes, may have less alternative uses but the availability is still difficult to predict. It is also difficult to assess individual farmers/suppliers intentions with land use, as discussed in Chapter 10. This will clearly affect biomass supply, hence the need to assess the barriers and drivers to a greater uptake of bioenergy production. This constraint is very difficult to completely overcome as these factors are affected by a complex interaction of agriculture, forestry, industry and waste management (Faaij, 2006). This element of subjectivity should be taken into account when interpreting the results.

Biomass resources are affected by geography and the local environment. How easily a particular biomass resource can be accessed is therefore directly related to its location. For example some biomass may be located on a steep slope or in a remote area; hence its use for bioenergy is restricted by practical geography and economics. Related to this is the dispersed nature of biomass which is a limitation of any resource assessment, i.e. the total biomass available is summarised for the region but in reality it is not in one place. A further limitation could thus be interpreted as taking the South West region as a whole and not breaking it down into much smaller geographical areas (such as performed by Aylott *et al., 2008;* Lovett *et al., 2009*). Spatial resource assessments could therefore be employed in future resource assessments using geographical information systems (GIS).

The scope of the resource assessment is a limitation since the whole of the UK was not included. However valuable results have been produced which can help inform bioenergy policy in the South West region. The present study did not assess other regions due to limitations in scope and resource constraints. Future studies could therefore apply the methodology outlined to complete biomass resource assessments for other parts of the UK.

To complete this resource assessment it was necessary to rely on several data sources. This was sufficient for the scope of the work due to the many excellent nationally maintained data sets. Nonetheless a more detailed study could have been completed if the resource constraints could be overcome and additional primary data was collected. A limitation of this study could be that it was not always possible to assess the quality of the data used. The development of the UK bioenergy industry will require this sort of information in order to make informed decisions about bioenergy schemes. Therefore good quality data on the biomass resource available is crucial for future bioenergy development.

11.4 LIFE CYCLE ASSESSMENT (LCA)

Two main LCA studies were undertaken in this thesis. Firstly a cradle-to-farm gate LCA of the perennial energy crops Miscanthus and short rotation coppice (SRC Willow) was completed. A second LCA of biomass gasification using wood waste was completed to assess as the chosen bioenergy conversion pathway. Results from the two LCA studies were bought together to assess the effects of using perennial energy crops with transportation instead of wood waste for biomass gasification.

11.4.1 Implications of LCA findings for perennial energy crops

Life cycle impact assessment (LCIA) results showed that for both crops the most important impact categories were fossil fuel depletion, climate change, particulate matter formation and agricultural land occupation. Acidification, eutrophication, and ecotoxicity can also be potential issues when fertilisers are used, and water depletion is an issue when irrigation is required. This confirms the need for net energy analysis and greenhouse gas (GHG) balance studies of bioenergy systems, but also highlights the use of LCA to assess a range of potential environmental impacts (Royal Society, 2008).

Despite these potential issues, for the impact categories assessed, perennial energy crops caused lower emissions and resource use than annual crops on a per hectare basis. However this is not a straightforward issue to conclude on as it is very complex to model the additional pressures on land use caused from an increase in demand from energy crops. The appropriate siting of energy crops is therefore key if sustainable agricultural practices are to be pursued (DEFRA, 2007d; EEA, 2007).

For both crops fossil fuel depletion was found to arise primarily from diesel used in farm machinery and in the production of agro-chemicals. GHG emissions and particulate matter formation were closely related to fossil fuel use. Hence minimising the use of diesel and inorganic chemicals offers one of the best ways to reduce the environmental effects of perennial crop production. Such options as using biodiesel or biogas in farm machinery could reduce the direct use of fossil fuels, and using organic fertilisers would decrease their indirect use.

Agricultural land occupation is a more complicated impact which arises from the growth of perennial energy crops. Land availability is limited both in the UK and abroad which limits the amount of crops which can be grown. By growing perennial energy crops on existing agricultural land, it is possible that other food and feed crops may be displaced (so-called indirect land use change). This means that whilst many of the potential impacts from perennial energy crops may be lower than those from annual food crops, the impacts which arise from the displaced crops will still occur. In other words using UK agricultural land for perennial energy crops could increase the total impact of agricultural production. Crops and livestock previously using land now used for energy crops may need to be cultivated elsewhere, which implies that the selection of land on which perennial energy crops are grown is critical (DEFRA, 2007d).

In ReCiPe the endpoint indicator for agricultural land occupation is damage to ecosystem diversity (Goedkoop *et al.*, 2009). It is the number of species lost per year which gives an indication of the potential damage caused from land use. Whilst this characterisation model is far from perfect it does give a useful insight into the potential issues which arise from agricultural land occupation, i.e. species diversity. One of the key concerns regarding bioenergy crops is the loss of biodiversity. This concern is due to monocultures being less stable than forests and requiring increased energy inputs, such as fertilisers, to maintain productivity. To mitigate this issue, IEA (2002) suggests retaining patches/riparian corridors of natural vegetation as well as re-establishing native vegetation.

When compared to annual crops, dedicated perennial energy crops may have the added benefit of providing certain ecosystem services, e.g. carbon sequestration, biodiversity enhancement, enhancement of soil and water quality (Rowe *et al.*, 2009). The value of these services will depend on the particular bioenergy system in question and the reference land use that it displaces (St. Clair *et al.*, 2008). For example, these benefits will be high for mixed species woodland planted into a cropping area which has suffered from land clearing whilst, on the other hand, if native tropical forests are displaced by bioenergy crops, the value of ecosystem services may be reduced.

When the contribution of different life cycle stages is considered, for Miscanthus it is the harvesting and baling stage which is most intensive. This is an annual operation and thus uses more energy and resources than the establishment of the crop. For SRC Willow, harvesting is also an intensive stage of production compared to establishing it. However it is the use of inorganic fertilisers and herbicides which contributed most to the potential environmental impacts from SRC Willow. This also holds for Miscanthus when higher agro-chemical inputs are assumed, therefore the use of these should be avoided.

Farm machinery is considered to be an integral part of modern farming operations. Without this machinery it would not be possible to produce energy crops, such as Miscanthus, on a commercial scale (Huisman & Kortleve, 1994). However, many bioenergy LCA studies in the literature do not appear to include farm machinery. This may be because the relative impact is considered too small, that insufficient data is available, or simply it has not been made clear in the LCA report. Nonetheless, farm machinery is often left outside the system boundary in other LCA studies. It has been included in this study in order to make the LCA comprehensive. For arable crop production, several different kinds of machines and equipment are used. This machinery often has considerable size but a low operation time. Therefore it is important to include only the amount of machinery utilised in each farm operation in LCAs of agricultural systems. A finding from this LCA is that it is the use of farm machinery (i.e. diesel use) rather than its manufacture that makes the largest contribution to impact categories.

Results from the sensitivity analysis showed that increased used of agro-chemicals has the biggest effect on the potential environmental burdens from crop growth. The use of drying and irrigation also increased the LCIA results significantly. It can thus be recommended that perennial energy crops should not be grown in regions which require irrigation. When drying is required this should be thought of at the biomass conversion plant design stage, as the use of heat from conversion processes can be used to dry feedstocks.

11.4.2 Implications of LCA findings for biomass gasification

Several key implications have arisen as a result of completing the LCA study of biomass gasification. The main environmental impact categories of concern are metal depletion, fossil fuel depletion, climate change, particulate matter formation, human toxicity and terrestrial ecotoxicity. When the potential damages are considered these issues are not significant. In comparison to the fossil fuel based energy systems that biomass gasification may replace, most potential impacts are much lower with the exception of metal depletion and the possible exception of particulate matter formation.

Metal depletion is a potential issue due to the high amount of steel used in plant construction. This study demonstrates that it is critical the impact of plant construction is taken into account, especially in small scale systems and when annual operating hours may be low. The relative impacts of plant construction can be reduced by using recycled materials, longer operating hours, longer lifetime, and recycling metals when the plant reaches the end of its life. On a 'per unit of energy produced basis' biomass gasification will generally cause higher metal depletion than fossil fuel based thermal electrical and heat generators. This is due to biomass gasification having lower capacity factors, smaller scale systems, lower calorific value of the fuel, and hence much lower total energy output.

Results for particulate matter formation are less conclusive due to insufficient primary data being available for producer gas combustion emissions from the plant. If UK emissions limits are assumed then particulates arising from the plant may become a potential issue. Suitable producer gas combustion emissions data from other biomass gasification plants could not be found in the literature and so this area requires further research.

Fossil fuel depletion arises as a consequence of UK grid electricity consumption for wood chipping, the parasitic load of the plant and natural gas used on start up. Some fossil fuel use is inevitable in every electrical generation system due to the energy requirements for manufacturing equipment. Additionally in this BGP, natural gas is consumed to initiate the gasification reactions and fossil fuels are used to prepare the feedstock ready for the gasifier. There may be some scope to reduce dependence on fossil fuel use by using alternative heat and pre-processing sources, such as renewable energy. However it does seem that some fossil fuel use is required which may question the sustainability of this technology, which is why the net energy analysis results are useful is assessing the ability of biomass gasification to displace fossil fuel use.

Global warming potential is closely related to fossil fuel use. A comparison of fossil fuel depletion and GHG emissions showed that biomass gasification performs better than fossil fuel based thermal electrical and heat generators. This is due to the biogenic carbon and renewable fuel source associated with biomass production.

Human toxicity and terrestrial ecotoxicity are potential issues with biomass gasification due to the composition of ash, indirect emissions from UK grid electricity use, and wastes associated with metal production. Further research into the composition of ash and the effects of spreading it onto agricultural land or disposing to landfill would be beneficial.

11.4.3 Implications of LCA findings for biomass gasification using perennial energy crops

Wood waste produced on-site has a much lower environmental load than perennial energy crops grown on agricultural land. This LCA study demonstrates that the source of biomass feedstock and how it is produced is a key determining factor in the potential impacts of a bioenergy system. Using the biomass gasification plant (BGP) case study as an example, the LCIA results for Miscanthus and SRC Willow were used and compared to wood waste. This established that for most impact categories using perennial energy crops made a substantial contribution.

Transportation did not make a notable contribution due to the BGP being small scale and only short distances being required.

Greenhouse gas emissions from crop cultivation contribute the most to the whole life cycle when biogenic emissions are not accounted for. When both fossil and biogenic emissions are considered crop cultivation to farm-gate has negative emissions which are released through producer gas emissions, i.e. carbon is sequestered in biomass growth and emitted via combustion (Guinee *et al*., 2009; Rabl *et al*., 2007).

Human toxicity emissions from Miscanthus were found to be comparable to the total from plant operation, whereas SRC Willow was almost double. Higher assumed fertiliser inputs and lower yields in SRC Willow accounted for the difference. As wood waste was considered a free resource, using cultivated crops greatly increases the human toxicity potential in the whole life cycle.

Metal depletion was found to be dominated by the plant construction, with crop growth increasing this category slightly due primarily to the allocation of farm machinery. When fossil fuel depletion is considered, crop growth and the agronomic practices employed are the key determining factor in the whole life cycle. For SRC Willow (with higher assumed inputs), crop cultivation contributes the most, for Miscanthus (with lower inputs) crop cultivation is more comparable to plant operation, whereas for waste wood (with minimial inputs) plant operation dominates. The biomass source, cultivation method and location can thus been seen as key determinants of the potential environmental impacts.

11.4.4 Limitations of LCA and case studies

11.4.4.1. General limitations of LCA

LCA does not consider local impacts, only regional and global impacts, which can be considered to be a possible limitation of any LCA study. This is particularly important with the cultivation of crops as the local environment and geography can vary considerably. Local soil quality, biodiversity, weather patterns and water availability are just some of the factors which ought to be evaluated when assessing bioenergy systems. LCA does not have scope for the incorporation of localised impacts, which should be considered when a LCA is commissioned (McManus, 2001). However, the very fact that LCA results are generic means that a clear advantage of LCA is that the data can be used anywhere. This means that the results generated in this thesis could be used alongside an Environmental Impact Assessment (EIA) to assess both regional and local impacts.

A further limitation which is difficult to overcome is that some reliance is placed on external data sets. This is necessary due to vast amount of data required to compile the life cycle inventory (LCI) and calculate the life cycle impact assessment (LCIA). Nonetheless it is not always possible to verify all of the upstream LCI data as the reporting of these datasets is often not completely transparent. Without inventory databases it would be very difficult to complete a LCA study due to the large and complex data required. Most LCA studies therefore use LCI databases, which are essentially a large collection of previous LCI studies. If they are published LCI studies help contribute to the ever expanding database of life cycle knowledge. As more LCIs are completed the number of products widens, and more data becomes available.

When modelling a product environmental impacts can be evaluated based on one item of the product as the functional unit. When modelling a system, it is much more complex to model the environmental impacts due to the number of variables in the system. For example, 1 MJ of electrical output from the system is affected by various factors including the feedstock composition, ambient temperature, the number of operating hours, etc. This can be considered a limitation in the modelling of any system, which is why all of the LCI, LCIA and sensitivity analysis results should be considered together.

Comparing across impact category indicators through normalisation is an optional step in LCA. The aim of normalisation in this study was to directly compare the relative importance of different impact categories. However, this direct application implies the acceptance of the ratios of different impacts as they exist today (Pennington *et al*., 2004). This means that the total current effects of fossil fuel depletion and ecotoxicological effects in Europe would be considered of equal importance. It is acknowledged that normalisation is not a perfect method, but the results found in this study are broadly in line with the potential environmental impacts expected from a bioenergy system. Hence this provides some assurance that the normalisation method applied is valuable.

11.4.4.2. Limitations in the LCA of perennial energy crops

A number of assumptions regarding agronomic practices and farming systems were needed to complete this study. As stated previously, the results obtained from the LCA are therefore subject to some variability. For example, diesel consumed in farm operations can and will vary depending on the terrain, driving methods and local conditions. Fertiliser use is also subject to variability as the nutrient requirements will depend on soil quality. Emissions arising from fertiliser use are also difficult to model as the local environment will determine the potential damages caused from nutrients leaching. Overall, it is the fact that ecosystems are dynamic and extremely varied which provides a limitation of this LCA study. However the LCA results do provide good indicators for potential issues.

Data on the manufacture of fertilisers is notoriously difficult to obtain due to a lack of published studies. This is perhaps due to the commercial confidentiality of the fertiliser manufacturers. Reliance has been placed on the data available in the Ecoinvent database for fertilisers. In order to verify this data, a review of previous studies was undertaken in the sensitivity analysis. This found that primary energy use and GHG emissions were broadly in line with other studies, indicating that the Ecoinvent data is suitable. However, the uncertainty associated with fertiliser manufacturing data, N_2O and other field emissions has not been included within this study.

A final limitation previously discussed is the environmental issues which are not included within a LCA study. Biodiversity is one such issue which is a consideration in the growth of perennial energy crops. Soil erosion, noise and odour are examples of other issues not assessed through a LCA. Although this study has not directly assessed these, a literature review found that in general perennial energy crops offer advantages for biodiversity when compared to annual crops. However, when forests or permanent grasslands are replaced biodiversity is likely to suffer as a consequence. Soil erosion is found to be reduced when perennial energy crops replace annual crops (Smeets *et al*., 2009). Odour and noise were not considered to be problems, although noise may be an issue at certain times of the crop life cycle such as harvesting. Dust may be an air quality issue arising from wood chipping.

11.4.4.3. Limitations in the LCA of biomass gasification

During the LCA study, the biomass gasification plant (BGP) was not fully operational and was still being commissioned. Some delays were also encountered due to the furniture manufacturer (which supplied the wood waste) going into administration during the global financial crisis in 2008. This caused difficulties in obtaining some primary data of the plant operation, which is a potential limitation of the research. Consequently not all of the LCI data for the BGP is primary data and several data sources were therefore required. The potential data uncertainty caused by this was assessed using the sensitivity analysis. However, it has been established that there is general lack of detailed LCI inventory data available on the construction and operational parameters of BGPs. Hence this thesis provides a vital contribution to the knowledge of biomass gasification. The main areas where LCI data is lacking constitute areas for further research, and are highlighted in Chapter 12.

Plant operating difficulties would have an affect on the LCA findings. Maintenance of the plant has not been fully accounted for in this study as this is somewhat unknown. This can be considered a limitation and should therefore been considered in more detail in future LCA studies. Hopefully the maintenance requirements of this technology will become better known over time as more working knowledge is obtained. This has certainly been the case in more established renewable energy sectors such as wind power.

Results obtained in modeling a system are subject to more variability than an individual product, as discussed above. This is particularly true for this study as illustrated by the difficulties encountered in obtaining some primary data. A limitation is therefore the direct releases arising from the plant operation. These problems were addressed by using data from the literature, but this limitation has helped to identify some areas where further research is required. These areas where better reporting of plant operation characteristics would be beneficial are highlighted in Chapter 12.

The weight of materials is the biggest determining factor in LCIA results for plant construction. For example, although instruments used in the plant are numerous and use a variety of materials, they weigh very little in comparison to the bigger parts of the plant. This means that they contribute only a small amount to each impact category. It is however likely that specialist manufacturing is required to produce many of these instruments. This information is lacking in the inventory databases used and through contacting companies.

Ancillary equipment or high energy use are examples where using weights and average manufacturing data may not been appropriate. In this LCA it was decided to leave electrical specifications outside the boundary due to lack of appropriate inventory data. If more detail was available on processes used, e.g. specific information on energy use, wasted materials and emissions, then this may impact on results. As such it is mainly the weight of materials which determines potential impacts, which is a limitation of this LCA.

11.4.5 LCA and other Environmental Management Tools

LCA is just one of a number of different environmental assessment tools. Some of these tools focus more on physical metrics, such as Ecological Risk Assessment (ERA), Environmental Impact Assessment or Thermodynamic (energy or exergy) analysis, whilst others are more focused on economic metrics such as Cost-Benefit Analysis (CBA) (see for example, (Hammond & Winnett, 2006). Each technique of environmental appraisal and valuation plays an important role in the context of sustainability assessment. LCA can be viewed as part of a family of environmental management tools and should not be considered in isolation. LCA complements the other tools but it can also be used as a stand-alone tool. McManus (2001) describes how LCA can be poor at identifying specific environmental impacts as it considers impacts towards categorised issues rather than to a specific receiving environment.

Another term often used to describe the tools outlined above is environmental systems analysis. This framework divides environmental systems into three systems: the social system, the technical system and the natural system (Baumann & Tillman, 2004). Each of these systems is interrelated and LCA methodology fits well within this framework. Technical systems are modelled in the inventory analysis, but the products and services are managed and controlled by social systems. Similarly, technical systems use resources from natural systems and they release wastes and pollutants to the natural environment. These changes are modelled in the characterisation stage of LCA. The extent to which changes in the environment become problematic is a matter for social systems to decide. As LCA models all three systems, it is multi-disciplinary. For example, inventory analysis requires engineering skills; impact assessment uses natural science and social sciences are used in performing weighting. It can therefore be argued that LCA is the most comprehensive of the environmental management tools.

11.5 NET ENERGY ANALYSIS

The life cycle inventory (LCI) data and system boundaries for the perennial energy crops and biomass gasification were applied to the net energy analysis study. This allowed the calculation of various net energy analysis metrics including the gross energy requirement (GER), energy gain ratio (EGR), energy requirement for energy (ERE) and the energy payback period (EPP). These metrics were used to assess the energy conversion efficiency of the chosen bioenergy pathways, and the delivered energy outputs. Results were compared against other bioenergy pathways and fossil fuel based energy systems to show that biomass gasification performs well. Perennial energy crops were also found to have much higher EGRs than annual crops.

11.5.1 Implications of the net energy analysis

Positive EGRs (and hence low ERE) were found for each of the bioenergy systems studied. This finding shows that biomass gasification can generate sufficient renewable energy for heat and power to help displace some use of fossil fuels use. However, the use of fossil fuel energy in some direct and indirect aspects of the plant operation does question the long term sustainability of this technology. This may be less of an issue as the UK electricity sector strives to become low-carbon, or if alternative energy sources can be used. Energy payback periods are good and are less than one year when wood waste is used. This increases to over 4 years when SRC Willow is used due to the time required to establish the crop. These EPPs were found to be comparable to and more favourable than some other renewable energy sources (Allen, 2009).

Perennial energy crops provide a very suitable source for biomass gasification in terms of the EGR and ERE. They have much higher EGRs than various annual crops. Wood waste and other waste products produce better results for EPP as these resources are readily available and do not require cultivation. Fossil fuels cannot break-even in terms of EPP as the ERE is always greater than unity, this is a clear advantage of using biomass sources.

Net energy analysis results highlight the importance of using the useful heat to maximise the EGR. For example, the EGR almost doubles when 50% of the heat is consumed and nearly triples when all of the heat can be utilised.

The GER of a product or system is often used as a screening indicator for environmental impacts (Huijbregts *et al*., 2005). Furthermore, GER values can be used to compare the results of a detailed LCA study to others where only primary energy demand is reported. A final use of GER results is to use them as a plausibility check since it is quite easy to judge on the basis of GER whether or not errors have been made. In this thesis the GER results have helped confirm many of the LCA findings and compare to other LCA studies.

11.5.2 Limitations of the net energy analysis

Data on the GER can form an important basis from which to point out the priorities for energy saving potential in the bioenergy system. This involves energy consumption data from the complex relationship between design, construction, operation, and disposal. A limitation of this study is that more detailed energy consumption data could not been obtained. For example, the parasitic load of the plant was given as 25kW, but the breakdown of this for individual items of electrical equipment was not obtained. This detailed information would be particularly helpful when assessing the improvement potential for the plant operation.

GER results in the net energy analysis have separated out the different energy resources. However the metrics calculated have used the total sum of these sources. This is a potential limitation as uncertainties exist in the characterisation of different energy resources (Frischknecht *et al*., 1998). For example, there is much debate surrounding the calculation of the energy content of uranium fuel for nuclear power (Frischknecht *et al*., 2007). As diverging concepts exist for the calculation of GER this should be considered when the sum total is used for the net energy analysis metrics.

Exergy analysis has not been performed in this thesis. However, it would provide valuable results alongside the net energy analysis in terms of assessing the quality of the energy produced. This would be particularly relevant to the CHP system, and so constitutes a potential area for further research.

11.6 IMPLICATIONS FOR THE SOUTH WEST REGION

This thesis has shown that the South West region has abundant biomass resources and the farming capability to increase the utilisation of these. There is however a number of barriers which the region will need to address in order to maximise its bioenergy potential. With the abolition of the South West regional development agency it is unclear which organisation would be best placed to take on responsibility for bioenergy development. It appears that local authorities should work together with developers, farmers and suppliers if a desired increase in the uptake of bioenergy is to be achieved.

RegenSW estimate that the South West needs to install over 7,000MW (of heat and electricity capacity) to reach a 15 per cent target by 2020, with the region only reaching one per cent at present (RegenSW, 2010). This is a major challenge, but also a major opportunity for the region. This thesis has shown that bioenergy can contribute up to 5 per cent of the region's energy supply based on using the existing biomass resource. This represents a third of the total renewable energy target. The Revision 2020 targets anticipated over 500MW of installed bioenergy capacity in the region by 2020 (Capener *et al.*, 2005). With less than 150MW currently installed (which includes landfill gas and sewage gas) much more still needs to be done to support and drive forward the sector.

Of the available biomass resources in the region, producing biogas through anaerobic digestion (AD) is the most suitable technology (DEFRA, 2010a; Mezzullo, 2010). Biomass gasification is more suitable for feedstocks with lower moisture content. Biomass gasification may also have an essential role to play in future bioenergy production, particularly if local wood resources are utilised more widely. The uptake of biomass gasification projects would likely increase further if perennial energy crop production is expanded. For both technologies the use of CHP is a priority to maximise the economic and environmental benefits.

Biomass CHP plants are best suited to off-grid locations like rural communities and farms, where they can help reduce reliance on oil-fuelled heating. Thus they have good potential for the South West region. The location of these plants ought to be where (or close to) the location of the available feedstock. This implies AD is best suited to farms and locations where organic wastes and residues are disposed. BGPs are suited to places where wood (or similar) waste arisings occur, such as industrial by-products. As much of the biomass resource is dispersed smaller scale systems are more suitable than large scale. However the economics of small scale systems are less proven (Bio-Renewables, 2004).

11.7 SUMMARY

The UK aims to obtain 15% of all energy from renewable energy sources by 2020, requiring significant increases in renewable contribution to each of the 3 energy sectors: electricity, heat and transport. This thesis has shown that bioenergy can contribute to the electricity and heat sectors by maximising the existing unutilised biomass resource (transport was outside the scope of this research). To achieve this several barriers identified in this thesis will need to be overcome. For a significant increase in bioenergy production it is apparent that perennial energy crops will need to be grown on a wider scale in the South West.

These studies demonstrate that given the right economic conditions, a significant quantity of biomass feedstocks could be produced in England and Wales over the next decade. However, there are a number of barriers to the development of UK bioenergy which need to be addressed (Adams *et al*., 2011; Thornley *et al.*, 2009b). These include the significant up-front costs of establishment and lag period until significant returns are realised for both Miscanthus and SRC Willow (ADAS, 2008). For a large increase in perennial energy crops over the next decade there needs to be a significant expansion in the production of planting material and infrastructure to establish the crops. ADAS (2008) estimate that it would take 10 years to bring Miscanthus and SRC Willow into full production, and even with rapid expansion of the industry, this will not happen without long term political and end user commitment providing the confidence to invest.

The UK has a wide diversity of biomass resources (as identified in Chapter 5). This implies that there will be no one size fits all approach to bioenergy production, and the chosen conversion technology will depend on the local biomass resource. A range of bioenergy schemes will therefore be needed in any given region.

CHAPTER 12. CONCLUDING REMARKS, RECOMMENDATIONS AND FURTHER WORK

To establish the UK potential for sustainable bioenergy production a number of studies have been completed in this thesis. It has been demonstrated that to analyse the potential for bioenergy a range of engineering, geographical, scientific and social techniques are necessary. The methods applied in this thesis are essential in assessing both bioenergy holistically and individual bioenergy pathways. This chapter therefore provides the final conclusions of the work presented in this thesis. Firstly the rationale for attempting the research is explained, followed by an evaluation of the main contributions arising from addressing the research objectives, and issues encountered in undertaking the research. Some recommendations based on the research findings are provided along with consideration of the areas in which future work should be focussed. Finally the overall concluding remarks portray the closing views and final considerations regarding the future potential for sustainable UK bioenergy production.

12.1 RATIONALE

The term bioenergy refers to energy produced from biomass and encompasses a wide range of feedstocks, conversion technologies and end-uses. Bioenergy has the potential to reduce carbon emissions, reduce fossil fuel use and enhance energy security. Indeed, several studies and Governmental policies and strategies foresee bioenergy as playing an essential role in the UK energy sector up to 2020 and beyond (DECC, 2009b). If bioenergy production is to fulfil its potential then the carbon savings and displacement of fossil fuels must be proven. Additionally other environmental impacts such as particulate matter formation must be minimised. To assess a range of potential impacts, life cycle assessment (LCA) is a useful evolving methodology which allows several environmental issues to be analysed. This thesis therefore set about completing a LCA to analyse the potential environmental issues which could arise from an increase in UK bioenergy production.

It was appreciated early on in the research that bioenergy as a whole is too broad an area to assess the techno-environmental impacts using LCA. Time and resource constraints have limited the research to one individual bioenergy pathway albeit with different feedstocks. Hence the initial work focused on analysing biomass resources, identifying the bioenergy conversion technologies and evaluating both the barriers to and the drivers for UK bioenergy development. These holistic studies of bioenergy used stakeholder surveys and resource assessment techniques to appraise bioenergy as a whole. From this work a valuable knowledge of the present UK bioenergy situation was obtained. Additionally this research identified perennial energy crops and biomass gasification as potentially forming a crucial role in future bioenergy supply. Thus it was recognised that new information is required on the environmental implications of these aspects of bioenergy pathways.

Information on bioenergy systems is vital for uptake of projects to be appropriate and effective in the context of more sustainable energy production. Detailed information on the different aspects of bioenergy systems is also essential in terms of overcoming the barriers to development and promoting wider uptake of bioenergy.

12.2 CONTRIBUTIONS RESULTING FROM THE RESEARCH

At the beginning of this thesis a range of objectives were defined to address the overall aims of the research (see Chapter 1). A brief evaluation of the main contributions arising from addressing these objectives is summarised here to consolidate the value of the completed research.

12.2.1 To outline relevant fundamental aspects of different bioenergy systems, describe the relevant terminology, and outline potential gaps in bioenergy research knowledge

There exists a wide range of potential bioenergy conversion pathways. This variety means that each conversion pathway should be assessed and treated individually rather than taking bioenergy as a whole. Hence environmental, technical, or economic assessments need to be performed for each pathway so rational decisions can be made as to which bioenergy systems are best suited to particular locations.

Previous LCA studies are limited and often incomplete. The inventory data and assumptions used are not always transparent. Environmental impact categories assessed are often limited to a few categories, but usually only energy and carbon assessments are completed. The LCA studies performed in this thesis therefore represent a comprehensive and detailed LCA of the perennial energy crops Miscanthus and SRC Willow, and a biomass gasification CHP plant.

12.2.2 To define the methodologies used in this interdisciplinary assessment of bioenergy production and use

A novel methodology was produced for assessing the barriers to and drivers for UK bioenergy development. This included identifying the factors affecting this development, and then assessing these through an original stakeholder survey.

Clear methods for undertaking a resource assessment for a given region have been defined. This includes potential data sources, availability constraints, competing uses and defining the resource equations for each biomass feedstock.

The application of LCA methodology to this UK biomass gasification plant is original. Furthermore no previous studies have used ReCiPe to assess the potential environmental impacts arising from perennial energy crop growth and biomass gasification.

Several net energy analysis metrics were defined which have been applied to the case studies. This produced several results such as the displaced EGR and EPP which have previously not be calculated for a biomass gasification plant.

12.2.3 To identify the barriers to and drivers for UK bioenergy development, and suggest ways in which the barriers may be overcome

It was established that the main factors to successful project implementation for the bioenergy supply chain are economic. Technology, resource availability, legislation and perceptual challenges are also important. However it was also identified that reducing carbon emissions and fossil fuel dependence was imperative to each stakeholder group. Hence the main conclusion is that for bioenergy schemes to be successful they must be both economically attractive and environmentally sustainable. This provides helpful findings to both Government policy makers and actors within the bioenergy supply chain. These findings should be accounted for when new bioenergy projects are being considered. A number of ways in which the Government may address the barriers identified were also included in Chapter 4.

12.2.4 To quantify the existing available biomass resource in the South West of England, evaluate how this may change over time, define resource equations for each feedstock, and identify the potential end uses

Current bioenergy production in the region is dominated by wastes, in particular landfill gas and sewage sludge are used for electricity generation. There is however a significant underutilised resource available which could be used for bioenergy production. The most significant of which arise from farm wastes due to the large agricultural sector in the region, with municipal, commercial and industrial wastes also widely available. The use of wastes is however restricted by the practicalities and economics of collection.

For a large increase in the biomass resource future supply may be increased by the growth of perennial energy crops. The present uptake of these crops was found to be low, but several studies and Governmental strategies indicate a large increase in future energy crop cultivation. There may be scope to grow between 24,000-57,000ha without a significant impact on food production. However, the likelihood of this and potential displacement of food crops is affected by a complex web of farmers decisions, economic conditions, global supply chains, world commodity prices, environmental legislation and a number of other social, economic and environmental factors.

Bioenergy is far from reaching its potential given the resources available. There is a sizeable underutilised biomass resource available, but the barriers analysed would evidently need to be overcome. Overall there are diverse supplies of biomass feedstocks available both currently and in the future. Therefore a range of conversion technologies are needed to utilise these resources. This demonstrates plainly that there is sufficient scope for the development of various bioenergy projects both in the South West and throughout the UK.

12.2.5 To assess the potential environmental impacts, using LCA, of an increase in perennial energy crop production (Miscanthus and Willow) for use in bioenergy systems

Life Cycle Impact Assessment (LCIA) results showed that potential environmental issues for both crops include fossil fuel depletion, climate change, particulate matter formation and agricultural land use. Most of the impacts arise from the use of farm machinery and agro-chemical inputs. However when compared to annual food crops (e.g. wheat or oilseed rape) these impacts were found to be much lower primarily due to less annual operations and lower inputs. Hence it can be concluded that from an environmental LCA perspective perennial energy crops have a lower impact than the annual crops they would likely replace. A caveat to this which is very complex to accurately assess, is land use. Due to the limited amount of land available, replacing existing farm land for energy crops will likely put additional pressures on ecosystem services, since annual food crops may need to be grown elsewhere.

Another possible exception is the localised impacts which are not assessed in LCA, such as biodiversity, local water and air quality, etc. Results are therefore less conclusive when the local environment is considered. Acidification and eutrophication are examples of impacts which can affect the local environment. These potential issues were found to become important when fertiliser use in crop growth is high. Water use may also be an issue in some areas with insufficient rainfall. When irrigation is required, the environmental pressures from crop growth increase significantly.

12.2.6 To examine the potential life cycle environmental impacts of a biomass gasification plant using LCA and net energy analysis

LCIA results revealed that potential environmental issues include fossil fuel depletion, metal depletion, climate change, particulate matter formation and ecotoxicity. These issues arise from different aspects of the plant construction and operation, as discussed in Chapters 8 and 11. This LCA has produced a number of results which have not previously been calculated for similar bioenergy systems. By assessing a number of different impact categories this study provides a broader scope. The LCA case studies in this thesis also provide more detailed findings since the LCIA results are given at both the midpoint and endpoint. Hence an indication of potential damages is presented alongside the LCI. This type of data may become increasingly important if Government's become more concerned with issues such as water use or toxicity. The political focus to date appears to be largely regarding reducing reliance on fossil fuels and climate change.

The net energy analysis revealed that biomass gasification CHP offers positive results which can help displace some use of fossil fuels. Benefits of biomass gasification are maximised when the useful heat produced is consumed.

Whilst there are a number of energy and carbon assessments of bioenergy pathways in the literature these have tended to focus more on biofuels for transport. Additionally previous energy analyses generally only calculate the net energy balance of the system. Therefore by applying a range of net energy analytics (ERE, EGR and EPP) to biomass gasification this provides a contribution to the knowledge. No previous studies have assessed the EPP or indeed the displaced EGR and EPP metrics.

12.2.7 To incorporate the analyses of perennial energy crops and biomass gasification to expand the system boundaries and assess the whole life cycle to include crop growth and transportation

It was found that crop cultivation contributed significantly to the overall impact of the BGP, whereas transportation did not. This finding demonstrates the value of accounting for all life cycle stages and shows that the choice of biomass feedstock will be a key determining factor in sustainable bioenergy production.

Comparisons of some impact assessment results to other energy systems were not always possible due to the lack of previous studies found. This highlights the importance of undertaking this study.

12.3 ISSUES ARISING IN UNDERTAKING THE RESEARCH

In undertaking any research project some issues are likely to arise. To make the research findings transparent a brief summary of the main issues encountered in this research is provided here. These should be considered when interpreting the results presented in this thesis. No issues of concern were found in studying the barriers to bioenergy development, although it was acknowledged that barriers may vary for different bioenergy pathways. In the biomass resource assessment it was necessary to estimate the availability and competing uses of several biomass sources. This inevitably leads to more qualitative results which should be taken into account when interpreting findings.

In the LCA case studies the main issues stem from the assumptions made in compiling the LCI, reliance on databases and the methods applied in the LCIA stage. From Chapters 6 and 7 it is apparent how much data is required in the LCI. It is clear that the subsequent LCIA results can vary with different LCI data; hence the initial LCIA results should be interpreted in conjunction with the sensitivity analysis. One issue encountered in compiling the LCI for the biomass gasification plant (BGP) operation was that the BGP had not been commissioned at the time of the research. This was discussed in Chapter 11, so further explanation is not warranted here.

Relying on databases is essential in a LCA but can also be problematic as the data may be out of date and it is not always possible to verify the underlying published data. Finally, the methods applied in life cycle impact assessment methodologies (LCIAM) do have some issues. These occur due to the fact that the environment and ecosystems are extremely complex to accurately model. This will always be a potential issue with LCIAM so it is important to ensure the most up to date and peer-reviewed studies are used in a LCA study. It also highlights the need to ensure that the environmental models used in LCIAM are continually improved and updated as new information becomes available.

12.4 RECOMMENDATIONS

A few recommendations have become apparent from undertaking the present research. These are summarised here with a brief explanation for each:

1. **Individual bioenergy pathways should be treated separately**

It is apparent from this research that bioenergy in its entirety is too diverse and complex to assess as a whole. For example, biomass gasification of wood is a very different technology and process to anaerobic digestion of animal manures; hence the energetic output, resources used, economics and potential environmental impacts are different. Therefore it is recommended that individual bioenergy pathways including feedstock and technology are assessed, discussed, and treated by academics, policy makers and in the literature as such, rather than referring to bioenergy as a whole. This may help overcome public perception barriers, and should allow for more rational and informed decision making surrounding bioenergy policy.

2. **Mechanisms to link farmers and developers would be beneficial**

By assessing the barriers to bioenergy development it was found that one of the biggest risks to developers was the security of feedstock supply. Similarly a barrier to farmers growing perennial energy crops was the risks associated with long term contracts. Hence mechanisms to connect these two stakeholders would help to remove this barrier.

3. **Mechanisms to promote alternative biomass feedstocks, such as farm wastes, ought to be considered**

Results from the biomass resource assessment showed that wastes and residues are some of the most abundant currently available biomass sources. Wood waste was also shown to have lower environmental impacts than using crops in the LCA. Land availability is an issue which can be avoided where wastes are utilised for bioenergy. The ultimate applicability of all biomass conversion technologies is restricted by the quantity of feedstocks that can be made available, hence maximising biomass arisings from existing industries and supply chains should be encouraged where appropriate.

4. **Data sets for biomass availability should be created and maintained**

There are a number of existing data sets available at a national level, such as agricultural statistics, woodland inventories and waste flows. To help match up the biomass supply with developer and end-user demand it would be useful for the Government to create and maintain one data set which oversees a range of biomass feedstocks. This would involve joining up data from different Government departments and agencies, but would also require information from local authorities, industry bodies and companies. Transparent, accurate and available information of this type is critical for a structured, organised and rational approach to the sustainable development of the bioenergy industry.

5. **Life cycle inventory data available in databases and used in LCA studies should be transparently reported**

As LCA studies are data intensive and time consuming, transparency of reporting (data used, assumptions and system boundaries) is critical in providing meaningful results. Where LCI data is transparent it facilitates ease of use in future studies and for the present study allows comparison with other bioenergy pathways.

6. **LCA results should be consistently reported to allow comparison**

When presenting results many studies use different measurements, this is particularly apparent with carbon or GHG emissions. It is therefore recommended that LCA results should be presented in a consistent way to aid comparison and interpretation.

7. **Agro-chemical inputs should be minimised in perennial energy crops to decrease the potential environmental impact**

Fertiliser and herbicide use has a large effect on LCIA results. Their use should be avoided or minimised in order to maximise the benefits of bioenergy production.

8. **Local impacts should be assessed before planting perennial energy crops**

LCA is not the correct tool for assessing potential impacts on a specific location (receiving environment). Therefore, the suitability of the local environment should be considered before land is used for growing perennial energy crops.

9. **Monitoring and measurement of plant operation characteristics**

In undertaking this research it has become apparent that more data should be available on plant operational characteristics. For the biomass gasification plant studied in this thesis it is recommended that improved energy management for both inputs and outputs in the system should be exercised. As a demonstration plant they should be keen to be a test case for producing information on all aspects of plant operation. This includes such data as energy mass balance, producer gas composition, ash composition, water composition, emissions from combustion, flow rates, pressure, etc. More technical knowledge of biomass gasification is required in the UK if it is to become more widely used for biomass energy. This recommendation should be expanded to all biomass energy conversion systems to improve the information available.

10. **Improvement potentials identified in the LCA should be considered**

Several areas were identified with improvement potential in the LCA of perennial energy crops (see 6.4.2) and biomass gasification (see 8.4.3). To reduce the potential environmental burden of the bioenergy systems studied, the recommendations made in the LCAs should be followed.

11. **'Life cycle' studies of bioenergy production pathways should assess a range of environmental impact categories**

More attention should be paid to gathering the data needed for environmental impact categories such as acidification, eutrophication, human toxicity and ecotoxicity, as well as land use and its effects on biodiversity. Moreover, the areas of protection of human and ecological health need to feature more prominently next to those of climate change and energy resource depletion concerns. This would allow LCIA results (e.g. those from this thesis) to be compared to other studies and different bioenergy pathways. This will become increasingly important as sustainability assessments cover a broader range of criteria.

12.5 FURTHER WORK

This thesis has identified some areas in which to focus further research in order to build upon and expand the present research, these can be summarised as:

Technical and economic barriers of individual bioenergy pathways
In the study of UK bioenergy development a number of barriers and drivers were identified and verified by key stakeholders. This study considered UK bioenergy as a whole, however further work could include a more detailed assessment of the barriers to the development of individual bioenergy pathways. For example, the barriers to anaerobic digestion of waste are likely to be very different to the barriers to the gasification of perennial energy crops.

Geographical based resource assessment
A more detailed geographical study, i.e. resource per km^2, could be performed to account for the local and dispersed nature of biomass. This might include a survey of landowners, measurement of yields over time, collecting primary data from companies, farmers, wood manufacturers, etc.

Resource assessment for other regions of the UK
Using the methodology outlined in Chapter 5, similar resource assessments could be carried out for other UK regions. This would allow for comparison between regions and the UK Government to take a more regional approach to bioenergy policy.

Assessment of the localised impacts of perennial energy crops
This should include the local biodiversity impacts of Miscanthus production, the impact of perennial crops on local watercourses, and local air quality.

Technical assessment of the gasification of Miscanthus and SRC Willow
Most of the available information in the literature on biomass gasification uses wood waste and residues as the feedstock. Less is known about the actual technical performance of Miscanthus and SRC Willow. For example, producer gas composition, ash composition, particulates, NO_x, etc. Therefore further technical studies should assess the actual performance data from the operation of gasification plants using a range of feedstocks.

Detailed analysis of biomass gasification plant operational characteristics

This is related to recommendation 9 above. Further research could be undertaken into plant operational characteristics for different gasification technologies. More published emissions data will help undertake future LCA studies and inform decision making.

The effect of varying levels of nitrogen fertiliser use in crops on the NO_x emissions from biomass gasification

Due to insufficient data this study could not conclude how higher nitrogen levels in the feedstock may effect subsequent NO_x emissions from gasification. Therefore further work could assess different amounts of nitrogen fertiliser input, how this effects feedstock composition, and what impact this has on the gasification process, i.e. producer gas composition and emissions from combustion.

Particulate matter emissions from biomass gasification

The present study and previous studies have tended to use emission limit values rather than actual primary data on particulate matter emitted from biomass gasification. Further research into particulate matter arising from the producer gas combustion is required.

Ash composition from biomass gasification

Some literature suggests ash may be inert, some suggests it has a use as a fertiliser, whilst it has also been found to cause potential impacts where metals and phosphates are found in ash. Data from the present study is inconclusive and so it would be a useful future study to assess the fertiliser value or potential impacts of ash disposal.

What scale of biomass gasification plant is most appropriate for the UK

Further research into how smaller scale systems compare to larger scale systems in terms of emissions per unit output. This effect of scaling could affect the relative impacts of plant construction, efficiency of biomass conversion, environmental releases, etc.

Economic assessment of biomass gasification

Economic assessment should be performed to complete the integrated assessment. There is a lack of published data available on the economics of biomass gasification. Hence there is an information need for the capital and operating costs, as well as cost-benefit analysis.

Further LCA studies of different bioenergy pathways

It is apparent that there is a need for more LCA studies to be undertaken on the growth of second generation energy crops, and on other biomass conversion technologies. This would allow further comparison of the different bioenergy pathways. Rational assessments could then be made of the best available feedstock and technology for a given location and bioenergy scheme.

12.6 OVERALL CONCLUDING REMARKS

This thesis has assessed the key environmental issues associated with biomass gasification. These issues include energy consumption, GHG emissions, land use, water consumption, eutrophication, biodiversity and air quality, as recommended by the Royal Society (2008). It is vital that these impacts are evaluated and quantified in order to provide a rational basis for assessing the long-term viability and acceptability of individual bioenergy pathways. The information presented in this thesis can be viewed as one piece of the bioenergy jigsaw, i.e. similar assessments also need to be undertaken for other feedstocks and conversion technologies to build up the complete picture for bioenergy production.

Resource assessment findings indicate that bioenergy can make a significant contribution towards renewable energy targets, and in filling in the gaps of more intermittent renewable energy sources. A review of GHG emissions for different energy systems also shows that bioenergy will play a role in meeting GHG reduction targets. Nonetheless a range of barriers and constraints have been identified which need to be addressed if the UK is to fulfil its bioenergy potential.

Operating difficulties encountered at the case study plant may indicate wider problems with biomass gasification as a technology. Some of the literature found does suggest that problems can arise in areas such as slagging and clinkering caused by ash and char (Bridgwater, 1995; IEE, 2007; Knoef, 2005; McKendry, 2002b). It is apparent that more technical knowledge is required in the UK for a wider uptake of biomass gasification. The operational difficulties encountered at the case study plant may have been avoided if additional local support, knowledge and expertise were available. Also although it is not possible to verify this, the low uptake of biomass gasification may be explained by the capital costs being prohibitively high. This combined with operating difficulties means that biomass gasification is seen as risky by investors. As there are several examples worldwide of successful BGPs (Knoef, 2005), many of the operating difficulties might be overcome with more operational experience and research and development support.

Bioenergy alone cannot be viewed as a silver bullet, it is one of the many wedges required to help address our energy challenges. Bioenergy production is ultimately resource limited which highlights one of the key issues with proposed expansion of the industry. When compared to other energy systems the primary issue with bioenergy is land use. With an increasing global population, the pressures placed on land to provide sufficient food and feed crops are clearly visible. Food riots experienced in developing countries in recent years has made the use of land for energy crops progressively more questionable. Other environmental pressures such as water availability, soil and air quality make the issues surrounding bioenergy increasingly multi-faceted.

These issues highlight the complexities surrounding sustainable development. On one hand is providing sufficient, affordable food for all in society. On the other is providing energy to cook, keep the lights on, and staying warm. These basic needs are directly affected by the economics of using land for different purposes, which in turn have varying implications on the environment. Overall it can be concluded that the available biomass and land resources should be utilised to balance out the needs of and maximise the benefits for both society and ecosystems. Government and society must make informed choices regarding production and consumption. This should be based on the potential damages caused to human health, ecosystems and resources, and not just simple supply and demand economics. Life cycle assessment helps provide this information to make more informed choices surrounding sustainable development.

In conclusion, bioenergy should be encouraged where the environmental benefits are proven, but caution should be employed when potential impacts may arise. Bioenergy has provided mankind with energy for thousands of years, and will continue to do so long into the future. The form and amount of bioenergy produced will depend on the decisions made regarding the best use of the available biomass resources. It is intended that this thesis is used to aide this decision-making process by providing crucial information about biomass resource availability, barriers to bioenergy development, perennial energy crops, biomass gasification and the potential environmental impacts arising from such bioenergy systems.

REFERENCES

Abbasi, T. & Abbasi, S. A. 2010. "Biomass energy and the environmental impacts associated with its production and utilization", *Renewable and Sustainable Energy Reviews*, vol. **14**, pp. 919-937.

Adams, P., Hammond, G., McManus, M.C., & Mezzullo, W. 2008. "Barriers to UK Bioenergy Development: Experiences from the South West of England", *Aspects of Applied Biology,* vol. **90**, Biomass and Energy Crops III, pp. 41-51.

Adams, P.W., Hammond, G.P., McManus, M.C. & Mezzullo, W.G. 2011. "Barriers to and drivers for UK bioenergy development", *Renewable and Sustainable Energy Reviews*, Vol. **15**, pp. 1217-1227.

ADAS 2008. *Addressing the land use issues for non-food crops, in response to increasing fuel and energy generation opportunities*. National Non-Food Crops Centre (NNFCC) Project 08-004, ADAS, Hereford.

AEA 2009a. *Evaluation of Opportunities for Converting Indigenous UK Wastes to Fuels and Energy.* Report to the NNFCC, contract no. ED45551, AEA Energy & Environment, Didcot.

AEA 2009b. *Bioenergy Review*. Science report: SC070001/SR1, AEA Energy & Environment, Environment Agency, Bristol.

Agricultural Engineering Association 2009. *UK tractor registrations: Market Share Analysis* [online]. Available from: http://www.aea.uk.com/index.php/industry-info/. Accessed 7th April 2010.

Agricultural Lime Association 2008. *Technical Information on Agricultural Lime Production & Use* [online]. Available from: http://www.aglime.org.uk. Accessed 21st August 2008.

Allen, S.R. 2009. *Micro-Generation for UK Households: Thermodynamic and Related Analyses.* PhD Thesis, University of Bath.

Andersons 2010. *A detailed economic assessment of anaerobic digestion technology and its suitability to UK farming and waste systems*. A report for the NNFCC no. 08-006, The Andersons Centre, Melton Mowbray.

ASABE 2008. *ASABE Standards: Engineering Practices Data, 55 D497.5*. American Society of Agricultural and Biological Engineers (ASABE), St. Joseph, USA.

Aylott, M., Casella, E., Tubby, I., Street, N.R., Smith, P., Taylor, G., 2008. "Yield and spatial supply of bioenergy poplar and willow short rotation coppice in the UK", *New Phytologist* vol. **178**, pp. 358–370.

Baumann, H. & Tillman, A.M. 2004. *The Hitch Hikers Guide to LCA. An Orientation in Life Cycle Assessment Methodology and Application.* Studentlitteratur, Lund, Sweeden.

Berndes, G., Hoogwijk, M., & van den Broek, R. 2003. "The contribution of biomass in the future global energy supply: a review of 17 studies", *Biomass & Bioenergy*, vol. **25**, pp. 1-28.

Biomass Energy Centre 2010. *Biomass Information Portal* [online]. Forestry Commission & Forest Research. Available from: http://www.biomassenergycentre.org.uk. Accessed 28th June 2010.

Bioregional 2003. *Straw availability in the UK.* BioRegional Development Group, Wallington, Surrey.

Bioregional 2008. *Biomass for London: wood fuel demand and supply chains*. London Energy Partnership, London. Available from: http://www.bioregional.com/files/publications/BiomassforLondon_Dec08.pdf. Accessed 18th October 2010.

Bio-Renewables 2004. *Small scale wood fuel heat and CHP options for South West England*. RegenSW, Exeter.

Boehmel, C., Lewandowski, I., & Claupein, W. 2008. "Comparing annual and perennial energy cropping systems with different management intensities", *Agricultural Systems*, vol. **96**, pp. 224-236.

Boman, U.R. & Turnbull, J.H. 1997. Integrated biomass energy systems and emissions of carbon dioxide, *Biomass and Bioenergy*, vol. **13**, pp. 333-343.

Borjesson, P. 1996. "Energy analysis of biomass production and transportation", *Biomass & Bioenergy*, vol. **11**, pp. 305-318.

Borjesson, P. 1999. "Environmental effects of energy crop cultivation in Sweden--I: Identification and quantification", *Biomass & Bioenergy*, vol. **16**, pp. 137-154.

Borjesson, P. & Berglund, M. 2006. "Environmental systems analysis of biogas systems--Part I: Fuel-cycle emissions, *Biomass & Bioenergy*, vol. **30**, pp. 469-485.

Bridgwater, A. V. 1995. "The technical and economic feasibility of biomass gasification for power generation", *Fuel*, vol. **74**, pp. 631-653.

Bridgwater, A. V. 2004. "Biomass Fast Pyrolysis", *Thermal Science*, vol. **8**, pp. 21-49.

Bridgwater, A. V., Meier, D., & Radlein, D. 1999. "An overview of fast pyrolysis of biomass". *Organic Geochemistry*, vol. **30**, pp. 1479-1493.

British Standards Institution 2005. *Natural gas – Calculation of calorific values, density, relative density and Wobbe index from composition*. BS EN ISO 6976:2005.

Buchholz, T., Luzadis, V. A., & Volk, T. A. 2009. "Sustainability criteria for bioenergy systems: results from an expert survey", *Journal of Cleaner Production*, vol. **17**, pp. S86-S98.

Bullard, M. & Metcalfe, P., 2001. *Estimating the energy requirements and CO_2 emissions from the periennial grasses Miscanthus, Switchgrass and Reed Canary Grass*. ETSU B/U1/00645/REP, DTI, London.

Capener, P., Scholes, H. & Ward, S. 2005. "Revision 2020 – South West Renewable Electricity, Heat and OnSite Generation Targets for 2020" [online]. Available from: http://www.oursouthwest.com/revision2020. Accessed 7th February 2009.

Carbon Trust 2004. *Combined heat and power for buildings*, Good Practice Guide GPG388, Carbon Trust, HMSO, London.

Carbon Trust 2010. *Introducing combined heat and power*, report no. CTV044, Carbon Trust, HMSO, London.

Carpentieri, M., Corti, A., & Lombardi, L. 2005. "Life cycle assessment (LCA) of an integrated biomass gasification combined cycle (IBGCC) with CO_2 removal", *Energy Conversion & Management*, vol. **46**, pp. 1790-1808.

Cherubini, F., Bird, N. D., Cowie, A., Jungmeier, G., Schlamadinger, B., & Woess-Gallasch, S. 2009. "Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations", *Resources, Conservation & Recycling*, vol. **53**, pp. 434-447.

Cogenco 2009. *Cogenco Combined Heat and Power Company* [online]. Available from: http://www.cogenco.co.uk/index.asp. Accessed 19th August 2009.

Concawe 2007. *Well-to wheels analysis of future automotive fuels and power trains in the European context, Version 2c*. European Commission, Joint Research Centre, Varese, Italy.

Confor 2010. *Wood fibre availability and demand in Britain 2007 to 2025.* Confederation of Forest Industries (Confor), Edinburgh.

Consoli, F., Allen, D., Boustead, I. et al, 1993. *Guidelines for life-cycle assessment: a 'Code of practice'.* SETAC Workshop, Sesimbra, Portugal, 31 March-3 April 1993, Society of Environmental Toxicology and Chemistry (SETAC).

CSL 2008. *National and regional supply/demand balance for agricultural straw in Great Britain*. Report prepared for the NNFCC, Central Science Laboratory (CSL), York.

Curran, M., 2006. *Life Cycle Assessment: Principles and Practice*. U.S. Environmental Protection Agency, Cincinnati, USA.

DECC 2009a. *Digest of UK Energy Statistics (DUKES) 2008*. Department for Energy and Climate Change, Her Majesty's Stationary Office (HMSO), London.

DECC 2009b. *UK Renewable Energy Strategy.* Department of Energy and Climate Change, HMSO, London.

DECC 2010a. *Feed-in Tariff, Government's response to the summer 2009 consultation.* Department of Energy and Climate Change, HMSO, London.

DECC 2010b. *Digest of UK Energy Statistics (DUKES) 2009*. Department for Energy and Climate Change, HMSO, London.

DECC 2010c. Energy Price Statistics [online]. Department for Energy and Climate Change, HMSO, London. Available from: http://www.decc.gov.uk/en/content/cms/statistics/prices/ prices.aspx. Accessed 28th November 2010.

DECC 2011. *Renewable Heat Incentive.* Department of Energy and Climate Change, HMSO, London.

DEFRA 2002. *Growing short rotation coppice: best practice guidelines for entrants to DEFRA's energy crop scheme*. Department for Environment, Food and Rural Affairs, HMSO, London. Available from: http://www.defra.gov.uk/erdp/pdfs/ecs/src-guide.pdf. Accessed 19th December 2008.

DEFRA 2004. *Rural Development Service Technical Advice Note 16. Rabbits: use of fencing to prevent agricultural damage*. Department for Environment, Food and Rural Affairs, HMSO, London.

DEFRA 2005. *Assessment of Methane Management and Recovery Options for Livestock Manures and Slurries*. Department for Environment, Food and Rural Affairs, HMSO, London.

DEFRA 2007a. *UK Biomass Strategy*. Department for Environment, Food and Rural Affairs, HMSO, London.

DEFRA 2007b. *Planting and Growing Miscanthus - Best Practice Guidelines For Applicants to Defra's Energy Crops Scheme*. Department for Environment, Food and Rural Affairs, HMSO, London.

DEFRA 2007c. *Waste Strategy for England.* Department for Environment, Food and Rural Affairs, HMSO, London.

DEFRA 2007d. *Opportunities and optimum sitings for energy crops within the South West region* [online]. Available from: http://archive.defra.gov.uk/foodfarm/growing/crops/industrial/ energy/opportunities/sw.htm. Accessed 25th September 2009.

DEFRA 2008a. *Estimating the Cost-effectiveness of Biofuels*. Department for Environment, Food and Rural Affairs, HMSO, London. Available from: http://www.defra.gov.uk/environment/climatechange/uk/energy/renewablefuel/pdf/biofuels-080414-2.pdf. Accessed 19th August 2009.

DEFRA 2008b. *Waste Wood as a Biomass Fuel – Market Information Report*. Waste Infrastructure Delivery Programme, HMSO, London.

DEFRA 2009. *Agriculture in the United Kingdom*. "Land Use and Livestock on Agricultural Holdings". Department for Environment, Food and Rural Affairs, HMSO, London. Available from: http://www.defra.gov.uk/statistics/. Accessed 29th January 2010.

DEFRA 2010a. *Accelerating the Uptake of Anaerobic Digestion in England: an Implementation Plan.* Department for Environment, Food and Rural Affairs, HMSO, London.

DEFRA 2010b. *Waste Statistics* [online]. Department for Environment, Food and Rural Affairs, HMSO, London. Available from: http://www.defra.gov.uk/evidence/statistics/ environment/wastats/archive/mwb200809.xls. Accessed 29th June 2010.

Deublein, D. & Steinhauser, A. 2008. *Biogas from waste and renewable resources: an introduction*. Wiley-VCH, Weinheim, Germany.

DfT 2008. *The Renewable Transport Fuel Obligations (Amendment) Order 2009.* Department for Transport, HMSO, London.

Doornbosch, R. & Steenblik, R. 2007. *Biofuels: is the cure worse than the disease?* Round Table on Sustainable Development, Organisation for Economic Co-operation and Development (OECD), Paris.

DTI 2007. *Meeting the Energy Challenge - Energy White Paper*. Department of Trade and Industry (DTI), HMSO, Norwich.

Dubuisson, X. & Sintzoff, I. 1998. "Energy and CO_2 balances in different power generation routes using wood fuel from short rotation coppice", *Biomass & Bioenergy*, vol. **15**, pp. 379-390.

E4Tech 2009. *Review of Technologies for Gasification of Biomass and Wastes*. Report to the NNFCC, project no. 09/008, E4Tech, London.

EAC 2008. *Are Biofuels Sustainable? – House of Commons Environmental Audit Committee (EAC)*, HC 76-I., Volume 1, HMSO, London.

ECN 2009. *Phyliss, database for the composition of biomass and waste* [online]. Energy Research Centre of the Netherlands (ECN). Available from: http://www.ecn.nl/phyllis/. Accessed 12th November 2009.

Ecofys 2005. *Planning and installing bioenergy systems : a guide for installers, architects, and engineers*. Deutsche Gesellschaft für Sonnenenergie, James and James, London.

Edwards, R. & Suri, M. 2007. *GIS based assessment of cereal straw resource assessment in the European Union*. Cereals Straw Resources for bioenergy in the European Union, Joint Research Centre & Institute for Environment & Sustainability (IES), Pamplona, 18-19 October 2006.

EEA 2006. *How much bioenergy can Europe produce without harming the environment?* European Environment Agency (EEA) Report No 7/2006. EEA, Copenhagen.

EEA 2007. *Estimating the environmentally compatible bioenergy potential from agriculture.* European Environment Agency (EEA) Technical Report No 12/2007. EEA, Copenhagen.

Elsayed, M. A., Matthews, R., & Mortimer, N. D., 2003. *Carbon and Energy Balances for a range of biofuels options*. ETSU B/B6/00784/REP, Department of Trade and Industry (DTI), London.

Elsayed, M. A. & Mortimer, N. D., 2001. *Carbon and Energy Modelling of Biomass Systems: Conversion Plant and Data Updates.* ETSU B/U1/00644/REP, Department of Trade and Industry (DTI), London.

Enagri 2010. *Bioenergy Weekly Market Report week ending 24th September 2010* [online]. Available from: http://www.enagri.info/market_data/weekly_reports. Accessed 10th October 2010.

Enagri 2011. *UK Bioenergy Maps* [online]. Available from: http://www.enagri.info/knowledge_base/maps.php . Accessed 17th January 2011.

Environment Agency 2004. *PG1/12(04) guidance note – Secretary of State's Guidance for Combustion of Fuel Manufactured From or Comprised of Solid Waste in Appliances Between 0.4 and 3MW Rated Thermal Input*. Environment Agency, Bristol.

Environment Agency 2010. *Biomass Environmental Assessment Tool (BEAT) v2* [online]. The Biomass Energy Centre, DEFRA and the Environment Agency. Available from: www.biomassenergycentre.org.uk/BEAT. Accessed 23rd April 2010.

EPA 2008. *Technology Characterization: Reciprocating Engines*. US Environmental Protection Agency, Washington.

EU 2006. *European Union (EU) Waste Framework Directive*. Brussels, Belgium. Available from: http://ec.europa.eu/environment/waste/legislation/index.htm. Accessed 6th July 2009.

European Commission 2001. *Green Paper: Towards a European strategy for the security of energy supply*. Brussels, Belgium.

European Commission 2004. *Towards a European knowledge-based bioeconomy – workshop conclusions on the use of plant biotechnology for the production of industrial biobased products.* EUR 21459. European Commission, Directorate-General for Research, Brussels, Belgium. Available from: http://ec.europa.eu/research/agriculture/library_en.htm. Accessed 17th October 2007.

European Commission 2008. *Directive of the European Parliament and of the Council "on the promotion of the use of energy from renewable sources".* COM(2008) 30 final, Brussels, Belgium.

European Commission 2009. *20 20 by 2020 Europe's Climate Change Opportunity.* Commission of the European Communities, Brussels, Belgium.

Evans, A., Strezov, V., & Evans, T. J. 2010. "Sustainability considerations for electricity generation from biomass", *Renewable and Sustainable Energy Reviews*, vol. **14**, pp. 1419-1427.

Faaij, A. P. C. 2006. "Bio-energy in Europe: changing technology choices", *Energy Policy*, vol. **34**, pp. 322-342.

FAO 2004. *Unified Bioenergy Terminology*. Food and Agriculture Organisation of the United Nations (FAO), Rome, Italy.

FAO, 2008. *Bioenergy, food security and sustainability towards an international framework*. Report HLC/08/INF/3, Food and Agriculture Organization (FAO), Rome, Italy.

Forestry Commission 2001. *National inventory of woodland and trees* [online]. UK Forestry Commission, Edinburgh. Available from: http://www.forestry.gov.uk/pdf/niengland.pdf/$FILE/ niengland.pdf. Accessed 24th October 2008.

Forestry Commission 2005. *SW Woodland & Forestry Framework 2005*. UK Forestry Commission, Exeter.

Forestry Commission 2007. *Woodfuel strategy for England* [online]. Available from: http://www.forestry.gov.uk/pdf/fce-woodfuel-strategy.pdf. Accessed 29th June 2008.

Forestry Commission 2008. *UK Timber Statistics* [online]. Available from: http://www.forestry.gov.uk/website/ForestStats2006.nsf/byunique/ukgrown.html. Accessed 20th September 2008.

Forestry Commission 2010. *Woodfuel Resource Tool* [online]. Available from: www.eforestry.gov.uk/woodfuel/. Accessed 20th February 2010.

Franzese, P., Rydberg, T., Russo, G., & Ulgiati, S. 2009. "Sustainable biomass production: A comparison between Gross Energy Requirement and Emergy Synthesis methods", *Ecological Indicators*, vol. **9**, pp. 959-970.

Frischknecht, R., Jungbluth, N., Althaus, H. J. et al, 2007. *Implementation of Life Cycle Impact Assessment Methods*, Ecoinvent report No. 3. Swiss Centre for Life Cycle Inventories, Switzerland.

Frischknecht, R., Heijungs, R., & Hofstetter, P. 1998. "Einstein's lessons for energy accounting in LCA", *The International Journal of Life Cycle Assessment*, vol. **3**, pp. 266-272.

Fthenakis, V. & Kim, H. C. 2008. "Land use and electricity generation: A life-cycle analysis. Renewable and Sustainable Energy Reviews", vol. **13**, pp. 1465-1474.

Fthenakis, V.M., Kim, H.C., Alsema, M. 2008. "Emissions from photovoltaic life cycles", *Environmental Science and Technology*, vol. **42**, pp. 2168–2174.

Gagnon, L., Belanger, C. and Uchiyama, Y. 2002. "Lifecycle assessment of electricity generation options: the status of research in year 2001", *Energy Policy*, vol. **30**, pp. 1267–1278.

Gallagher, G., 2002. *Development of a small-scale biomass CHP system*. A report for the DTI no ETSU B/U1/00678/REP, Sustainable Energy Ltd, HMSO, London.

Gigler, J.K., van Loon, W.K.P. & Sonneveld, C. 2004. "Experiment and modelling of parameters influencing natural wind drying of willow chunks", *Biomass & Bioenergy*, vol. **26**, pp. 507-514.

Gilbert, P., Thornley, P. & Riche, A. 2011. "The influence of organic and inorganic fertiliser application rates on UK biomass crop sustainability", *Biomass & Bioenergy,* vol. **35**, pp. 1170-1181.

Gill, B., Roberts, J., & Hartley N, 2005. *Biomass Task Force*. Department for Environment, Food and Rural Affairs, HMSO, London.

Goedkoop, M., Effting, S., & Collignon, M. 2000. *The Eco-indicator 99-A damage oriented method for Life Cycle Impact Assessment. Manual for Designers. Second edition*. PRé Consultants B.V., Amersfoort, The Netherlands.

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J. & Van Zelm, R. 2009. *ReCiPe 2008 – A life cycle impact assessment method which compares harmonised category indicators at the midpoint and the endpoint level*. First edition, Report I: Characterisation. Ministry of Housing, Spatial Planning and Environment (VROM), Netherlands.

Goglio, P. & Owende, P. M. 2009. "A screening LCA of short rotation coppice willow (Salix sp.) feedstock production system for small-scale electricity generation", *Biosystems Engineering*, vol. **103**, pp. 389-394.

Grogan P. & Matthews R., 2002. "A modelling analysis of the potential for soil carbon sequestration under short rotation coppice willow bioenergy plantations", *Soil Use Management*, vol. **18**, pp.175–83.

Grigal, D. F. & Berguson, W. E. 1998. "Soil carbon changes associated with short-rotation systems", *Biomass & Bioenergy*, vol. **14**, pp. 371-377.

Guinee, J. B., Heijungs, R., & van der Voet, E. 2009. "A greenhouse gas indicator for bioenergy: some theoretical issues with practical implications", *International Journal of Life Cycle Assessment*, vol. **14**, pp. 328-39.

Guinée, J.B.(Ed.), Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.A., de Bruijn, J.A., van Duin, R. & Hansen, E.M., 2002. *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards.* Kluwer Academic Publishers, Dordrecht.

Haines-Young, R. 2009. "Land use and biodiversity relationships", *Land Use Policy*, vol. **26**, pp. S178-S186.

Hammond, G. P. 2000. "Energy, Environment and Sustainable Development: A UK Perspective", *Process Safety and Environmental Protection*, vol. **78**, pp. 304-323.

Hammond, G. P. 2004. "Engineering sustainability: thermodynamics, energy systems, and the environment", *International Journal of Energy Research*, vol. **28**, pp. 613-639.

Hammond, G. P., Kallu, S., & McManus, M. C. 2008a. "Development of biofuels for the UK automotive market", *Applied Energy*, vol. **85**, pp. 506-515.

Hammond, G. P., McManus, M. C., & Mezzullo, W. G. 2008b. "A bioenergy resource assessment for the South West of England", *Proceedings of the Institution of Civil Engineers, Energy*, vol. **161**, pp. 159-173.

Hammond, G. P. & Waldron, R. 2008. "Risk assessment of UK electricity supply in rapidly evolving energy sector", *Proceedings of the Institution of Mechanical Engineers; Part A; Journal of Power and Energy*, vol. **222**, pp. 623-642.

Hammond, G. P. & Winnett, A. B. 2006. "Interdisciplinary perpespectives on environmental appraisal and valuation techniques", *Proceedings of Institute of Civil Engineers, Waste and Resource Management*, vol. **159**, pp. 117-130.

Harrison, R. M., 1999. *Understanding our Environment - An Introduction to Environmental Chemistry and Pollution (Third Edition)*. The Royal Society of Chemistry, Cambridge.

Hayashi, K., Okazaki, M., Itsubo, N. & Inaba, A. 2004. "Development of damage function of acidification for terrestrial ecosystems based on the effect of aluminum toxicity on net primary production". *The International Journal of LCA*, vol. **9**, pp. 13-22.

Heller, M. C., Keoleian, G. A., Mann, M. K., & Volk, T. A. 2004. "Life cycle energy and environmental benefits of generating electricity from willow biomass", *Renewable Energy*, vol. **29**, pp. 1023-1042.

Heller, M. C., Keoleian, G. A., & Volk, T. A. 2003. "Life cycle assessment of a willow bioenergy cropping system", *Biomass & Bioenergy*, vol. **25**, pp. 147-165.

Hertwich, E.G., Pease, W.S., McKone, T.E., 1998. "Evaluating toxic impact assessment methods: what works best?", *Environmental Science Technology*, vol. **32**, pp. A138-A144.

HGCA 2005. *Environmental impacts of cereal and oilseed rape cropping in the UK and assessment of the potential impacts arising from cultivation for liquid biofuel production.* Research Review No. 54. A report for the Home Grown Cereals Authority by the Central Science Laboratory (CSL), York.

Higman, C. & van der Burgt, M. 2008. *Gasification*. Gulf Professional Publishing, Oxford.

Hofbauer, H. 2007. "Conversion Technologies: Gasification Overview", *15th European Biomass Conference & Exhibition*, 7-11 May 2007, Berlin, Germany.

Hofstetter, P. 1998. *"Perspectives in life cycle impact assessment: a structured approach to combine models of the technosphere, ecosphere and valuesphere"*. Kluwer, Dordrecht, The Netherlands.

Hoogwijk, M., Faaij, A., van den Broek, R., Berndes, G., Gielen, D., & Turkenburg, W. 2003. "Exploration of the ranges of the global potential of biomass for energy", *Biomass & Bioenergy*, vol. **25**, pp. 119-133.

Huijbregts, M. A. J., Rombouts, L. J. A., Hellweg, S., Frischknecht, R., Hendriks, A. J., van de Meent, D., Ragas, A. M. J., Reijnders, L., & Struijs, J. 2005. "Is Cumulative Fossil Energy Demand a Useful Indicator for the Environmental Performance of Products?", *Environmental Science & Technology*, vol. **40**, pp. 641-648.

Huijbregts, M.A.J., Thissen, U., Guinée, J.B., Jager, T., Van de Meent, D., Ragas, A.M.J., Wegener Sleeswijk, A., Reijnders, L. 2000. "Priority assessment of toxic substances in life cycle assessment, I: Calculation of toxicity potentials for 181 substances with the nested multi-media fate, exposure and effects model USES-LCA", *Chemosphere*, vol. **41**, pp. 541-573.

Huisman, W. & Kortleve, W. J. 1994. "Mechanization of crop establishment, harvest, and post-harvest conservation of Miscanthus sinensis Giganteus", *Industrial Crops and Products*, vol. **2**, pp. 289-297.

IAEA 1994. *Net energy analysis of different electricity generation systems*. IAEA-TECDOC-753, International Atomic Energy Agency (IAEA), Vienna.

IEA 2002. *Sustainable production of woody biomass for energy* [online]. IEA Bioenergy Tasks 29, 30, 31 and 38. Available from: http://www.ieabioenergy.com/library/157_PositionPaper-SustainableProductionofWoodyBiomassforEnergy.pdf. Accessed 5th January 2011

IEA 2006. *The role of Soil Carbon in the GHG balance of bioenergy systems.* IEA Bioenergy Task 38, Joanneum Research, Graz, Austria.

IEA 2007. *IEA Bioenergy Task 34: Pyrolysis Principles* [online]. Available from: http://www.pyne.co.uk/?_id=76. Accessed 11th March 2008.

IEA 2009. *World Energy Outlook 2009*. International Energy Agency (IEA), Paris, France.

IEA 2010a. *Ash database*. IEA Bioenergy Task 32: Biomass Combustion and Co-Firing. BIOS Bioenergiesysteme GmbH Graz, Austria. Available from: http://www.ieabcc.nl/database/ash.php. Accessed 3rd February 2010.

IEA 2010b. ‘Biomass feedstocks for energy markets’ Long-Term Soil Productivity Study (LTSP). IEA Bioenergy Task 43, International Workshop "Sustainability across the supply chain of land-based biomass“, Kamloops, Canada.

IEE 2007. *Biomass gasification - State of the art description.* Gasification Guide, Intelligent Energy Europe (IEE), Graz, Austria.

IEE 2009a. *BAP DRIVER – European Best Practice Report: Towards National Biomass Action Plans*. Intelligent Energy for Europe (IEE), Contract No. EIE/07/118/SI2.467614. Available from: http://www.bapdriver.org/doku.php/best_practice. Accessed 27th July 2009.

IEE 2009b. Guideline for Safe and Eco-friendly Biomass Gasification. Intelligent Energy for Europe (IEE). Available from: http://www.gasification-guide.eu/. Accessed 7th April 2010.

IFIAS 1974. *IFIAS Workshop Report 6: Energy analysis, methodology and conventions*. International Federation of Institutes for Advanced Study, Ulriksdals Slott, S17171 Solna, Sweden.

IPCC 2007. *Climate Change 2007: The physical science basis – summary for policymakers.* Intergovernmental Panel on Climate Change (IPCC), Geneva.

ISO 2006a. *Environmental management - life cycle assessment - principles and framework*. Second Edition, EN ISO 14040, International Standards Organisation (ISO), London.

ISO 2006b. *Environmental management - life cycle assessment – requirements and guidelines*. Second Edition, EN ISO 14044, International Standards Organisation (ISO), London.

Johnson, P. 1999. *Fertiliser requirements for short rotation coppice.* ETSU Report B/W2/00579/REP/1, Department of Trade and Industry (DTI), HMSO, London.

Jones, M. & Walsh, M. 2001. *Miscanthus: For Energy and Fibre*. James & James, London.

Jonsson, A. & Hillring, B. 2006. “Planning for increased bioenergy use--Evaluating the impact on local air quality”, Biomass & Bioenergy, vol. **30**, pp. 543-554.

Jug, A., Makeschin, F., Rehfuess, K.E. & Hofmann-Schielle, C. 1999. “Short rotation plantations of balsam poplars, aspen and willows on former arable land in the Federal Republic of Germany. III. Soil ecological effects”, *Forest Ecology Management*, vol. **121**, pp. 85–99.

Jungbluth, N.(ed.), Emmenegger, M.F., Dinkel, F., Stettler, C., Doka, G., Chudacoff, M., Dauriat, A, Spielmann, M., Sutter, J., Kljun, N., & Schleiss, K. 2007. *Life Cycle Inventories of Bioenergy, Ecoinvent report No. 17.* Swiss Centre for Life Cycle Inventories, Switzerland.

Junginger, M., Bolkesji, T., Bradley, D., Dolzan, P., Faaij, A., Heinim, J., Hektor, B., Leistad, Ï., Ling, E., Perry, M., Piacente, E., Rosillo-Calle, F., Ryckmans, Y., Schouwenberg, P. P., Solberg, B., Trimborg, E., Walter, A. d. S., & Wit, M. d. 2008. “Developments in international bioenergy trade”, *Biomass & Bioenergy*, vol. **32**, pp. 717-729.

Jungmeier, G., Resch, G., & Spitzer, J. 1998. “Environmental burdens over the entire life cycle of a biomass CHP plant”, *Biomass & Bioenergy*, vol. **15**, pp. 311-323.

Kahle, P., Beuch, S., Boelcke, B., Leinweber, P. & Schulten, H.R. 2001. “Cropping of Miscanthus in Central Europe: biomass production and influence on nutrients and soil organic matter”, *European Journal of Agronomy*, vol. **15**, pp. 171–84.

Keoleian, G. A. & Volk, T. A. 2005. “Renewable energy from willow biomass crops: Life cycle energy, environmental and economic performance”, *Critical Reviews in Plant Sciences*, vol. **24**, pp. 385-406.

King, J.A., Bradley, R.I., Harrison, R. & Carter, A.D. 2004. *Carbon sequestration and saving potential associated with changes to the management of agricultural soils in England*. Soil Use Management, vol. **20**, pp. 394–402.

Knecht, W. 2008. “Diesel engine development in view of reduced emission standards”, *Energy*, vol. **33**, no. 2, pp. 264-271.

Knoef, H. 2005. *Handbook Biomass Gasification*. BTG biomass technology group, Enschede, Netherlands.

Koplow, D. 2006. *Biofuels – At what cost? Government support for ethanol and biodiesel in the United States*, Global Subsidies Initiative (GSI), International Institute for Sustainable Development (IISD), Geneva, Switzerland.

Kutas, G., Lindberg, C., & Steenblik, R. 2007. *Biofuels – At what cost? Government support for ethanol and biodiesel in the European Union*, Global Subsidies Initiative (GSI), International Institute for Sustainable Development (IISD), Geneva, Switzerland.

Lamlom, S. H. & Savidge, R. A. 2003. "A reassessment of carbon content in wood: variation within and between 41 North American species", *Biomass & Bioenergy*, vol. **25**, pp. 381-388.

Larson, E. D. 2006. "A review of life-cycle analysis studies on liquid biofuel systems for the transport sector", *Energy for Sustainable Development*, vol. **10**, pp. 109-126.

Lattimore, B., Smith, C. T., Titus, B. D., Stupak, I., & Egnell, G. 2009. "Environmental factors in woodfuel production: Opportunities, risks, and criteria and indicators for sustainable practices", *Biomass & Bioenergy*, vol. **33**, pp. 1321-1342.

Leach, G. 1975. "Net energy analysis -- is it any use?", *Energy Policy*, vol. **3**, pp. 332-344.

Lewandowski, I., Clifton-Brown, J. C., Scurlock, J. M. O., & Huisman, W. 2000. "Miscanthus: European experience with a novel energy crop", *Biomass & Bioenergy*, vol. **19**, pp. 209-227.

Lewandowski, I., Kicherer, A., & Vonier, P. 1995. "CO_2-balance for the cultivation and combustion of Miscanthus", *Biomass & Bioenergy*, vol. **8**, pp. 81-90.

Lieuwen, T., Yang, V., & Yetter, R. 2010. *Synthesis Gas Combustion: Fundamentals and Applications*. CRC Press, Florida, USA.

L'Observatoire des énergies renouvelables (Observ'ER) 2006. *Solid Biomass Barometer (Le baromètre Biomasse solide*). Available from: http://www.energies-renouvelables.org/observ-er/stat_baro/observ/baro182.pdf. Accessed 19th August 2009.

L'Observatoire des énergies renouvelables (Observ'ER) 2007. *7th report EurObserv'ER: State of Renewable Energies in Europe*. Available from: http://www.eurec.be/content/view/60/49/. Accessed 27th July 2009.

Lovett, A.A., Sünnenberg, G.M., Richter, G.M., Dailey, A.G., Riche, A.B., Karp, A., 2009. "Land use implications of increased biomass production identified by GIS-based suitability and yield mapping for Miscanthus in England", *Bioenergy Research*, vol. **2**, pp. 17–28.

Lunds Universitet 2003. *Toxicity of wastewater generated from gasification of woodchips.* Report for the Danish Energy Agency Follow-up Programme for Combined Heat and Power production (CHP), Department of Water and Environmental Engineering, Lund Institute of Technology, Lund, Denmark.

Makeschin, F. 1994. "Effects of energy forestry on soils", *Biomass & Bioenergy*, vol. **6**, pp. 63–79.

Mann, M. & Spath, P., 1997. *Life Cycle Assessment of a Biomass Combined-Cycle System.* National Renewable Energy Laboratory (NREL), Golden, CO, USA.

Mann, M.K. & Spath, P.L. 2001. "A lifecycle assessment of biomass co-firing in a coal-fired power plant", *Clean Production Processes*, vol. **3**, pp. 81-91.

Matthews, R. W. 2001. "Modelling of energy and carbon budgets of wood fuel coppice systems", *Biomass & Bioenergy*, vol. **21**, pp. 1-19.

Mattison, E.H.A. & Norris, K. 2007. "Intentions of UK Farmers toward Biofuel Crop Production: Implications for Policy Targets and Land Use Change", *Environmental Science Technology*, vol. **41**, pp. 5589-5594.

McCormick, K. & Kaberger, T. 2007. "Key barriers for bioenergy in Europe: Economic conditions, know-how and institutional capacity, and supply chain co-ordination", *Biomass & Bioenergy*, vol. **31**, pp. 443-452.

McKendry, P. 2002a. "Energy production from biomass (part 1): overview of biomass". *Bioresource Technology*, vol. **83**, pp. 37-46.

McKendry, P. 2002b. "Energy production from biomass (part 2): conversion technologies", *Bioresource Technology*, vol. **83**, pp. 47-54.

McKendry, P. 2002c. "Energy production from biomass (part 3): gasification technologies". *Bioresource Technology*", vol. **83**, pp. 55-63.

McLellan, R., 2000. *Design of a 2.5MW(e) Biomass Gasification Power Generation Module*. Report for the DTI: No. ETSU B/T1/00569/REP. Wellman Process Engineering Limited, HMSO, London.

McManus, M.C. 2001. *Life Cycle Assessment of Rapeseed and Mineral Oil Based Fluid Power Systems.* PhD Thesis, University of Bath.

Met Office 2009. South West regional average climate data 1971-2000 [online]. Available from: http://www.metoffice.gov.uk/climate/uk/sw/. Accessed 12th October 2010.

Mezzullo, W.G. 2010. *An Interdisciplinary Assessment of Biogas Production and the Bioenergy Potential within the South West of England.* PhD Thesis, University of Bath.

Monti, A., Fazio, S., & Venturi, G. 2009. "Cradle-to-farm gate life cycle assessment in perennial energy crops", *European Journal of Agronomy*, vol. **31**, pp. 77-84.

Mortimer, N.D. 1991. "Energy analysis of renewable energy sources, *Energy Policy*, vol. **19**, pp. 374–385.

Murray, C.J. & Lopez, A.D. 1996. *The global burden of disease: a comprehensive assessment of mortality and disability from diseases, injuries, and risk factors in 1990 and projected to 2020*. Global Burden of Disease and Injury Series Volume I, Harvard School of Public Health, World Bank, World Health Organisation, USA.

Natural England 2009a. *Energy Crops Scheme - Establishment Grants Handbook* [online]. Available from: http://www.naturalengland.org.uk/Images/ECShandbook3ed_tcm6-12242.pdf. Accessed 27th December 2009.

Natural England 2009b. Areas of Outstanding Natural Beauty [online]. Available from: http://www.naturalengland.org.uk/ourwork/conservation/designatedareas/aonb/default.aspx. Accessed 24th February 2010.

Natural England 2010. *Energy Crops Scheme Plantings*. Personal communication, Katie Vowles, Natural England, March 2010, Email.

Nemecek, T. & Erzinger, S. 2005. "Modelling Representative Life Cycle Inventories for Swiss Arable Crops", *The International Journal of Life Cycle Assessment*, vol. **10**, pp. 68-76.

Nix, J. 2003. *Farm Management Pocket Book*, 33rd ed. The Anderson Centre, Melton Mowbury, Leicestershire.

Nix, J. 2008. *Farm Management Pocket Book*, 38th ed. The Anderson Centre, Melton Mowbury, Leicestershire.

Nix, J. 2009. *Farm Management Pocket Book*, 39th ed. The Anderson Centre, Melton Mowbury, Leicestershire.

NNFCC 2010. Power Plants 2020 [online]. Available from: http://www.nnfcc.co.uk/crops-wood-waste/our-services/powerplants2020. Accessed 28th September 2010.

Nolan, A., McDonnell, K., McSiurtain, M., Carroll, J., Finnan, J., & Rice, B. 2008. "Conservation of Miscanthus sinesis giganteus in bale form", *Aspects of Applied Biology,* vol. **90**, Biomass and Energy Crops III, pp. 255-262.

NSCA 2006. *Biogas as a road transport fuel: An assessment of the potential role of biogas as a renewable transport fuel.* National Society for Clean Air and Environmental Protection (NSCA), Brighton.

NSRI 2008. *Soilscapes: soil thematic dataset* [online]. National Soil Resources Institute (NSRI), Cranfield University. Available from: http://www.landis.org.uk/soilscapes/. Accessed 30th October 2008.

OECD-FAO 2007. Agricultural Outlook 2007-2016. Organisation for Economic Co-Operation and Development, Food and Agriculture Organisation of the United Nations (OECD-FAO), Paris, France. Available from: http://www.oecd.org/dataoecd/6/10/38893266.pdf. Accessed 2nd February 2008.

OECD 2009. *Abstracts of agricultural tractor test search engine* [online]. Organisation for Economic Co-operation and Development (OECD), Paris, France. Available from: http://www2.oecd.org/agr-coddb/index_en.asp. Accessed 23rd February 2010.

Ofgem 2009. *Renewables Obligation: Guidance for licensed electricity suppliers (GB and NI)*. Office of Gas and Electricity Markets (Ofgem), London.

Ofgem 2010 [online]. *List of accredited power stations.* Available from: http://www.ofgem.gov.uk/Sustainability/Environment/RenewablObl/Pages/RenewablObl.aspx. Accessed 25th May 2010.

Oland, C. B. 2004. *Guide to Combined Heat and Power Systems for Boiler Owners and Operators*, Report no. ORNL/TM-2004/144, US Department of Energy, Oak Ridge.

ONS 2010. *South West Regional Profile – Environment* [online]. Office of National Statistics (ONS), HMSO, London. Available from: http://www.statistics.gov.uk/cci/nugget.asp?id=2324. Accessed 2nd July 2010.

Parkin, S. 2000. "Sustainable development: the concept and the practical challenge", *Proceedings of the Institution of Civil Engineers, Civil Engineering*, vol. **138**, pp. 3-8.

Pehnt, M. 2006. "Dynamic lifecycle assessment of renewable energy technologies", *Renewable Energy*, vol. **31**, pp. 55–71.

Pennington, D. W., Potting, J., Finnveden, G., Lindeijer, E., Jolliet, O., Rydberg, T., & Rebitzer, G. 2004. "Life cycle assessment Part 2: Current impact assessment practice", *Environment International*, vol. **30**, pp. 721-739.

Piterou, A., Shackley, S., & Upham, P. 2008. "Project ARBRE: Lessons for bio-energy developers and policy-makers", *Energy Policy*, vol. **36**, vol. 2044-2050.

Pre Consultants 2008. *Introduction to LCA with SimaPro 7*. Pre Consultants, Amersfoort, The Netherlands.

Rabl, A., Benoist, A., Dron, D., Peuportier, B., Spadaro, J., & Zoughaib, A. 2007. "How to account for CO_2 emissions from biomass in an LCA", *The International Journal of Life Cycle Assessment*, vol. **12**, p. 281.

Rajvanshi, A. K. 1986. "Biomass Gasification", *Alternative Energy in Agriculture*, pp. 83-102, CRC Press, New York.

RCEP 2004. *Biomass as a Renewable Energy Source.* Royal Commission on Environmental Pollution (RCEP), HMSO, London.

REA 2009. *Landfill Gas*. Renewable Energy Agency (REA). Available from: http://www.r-e-a.net/power/biomass-bioenergy/landfill-gas. Accessed 12th September 2010.

RegenSW 2008. *Survey of Renewable Electricity and Heat Projects in the South West of England* for 2008 [online]. Available from: http://regensw.co.uk/downloads/RegenSW_184.pdf. Accessed 15th August 2009.

RegenSW 2010. *Survey of Renewable Electricity and Heat Projects in the South West of England* for 2010 [online]. Available from: http://www.regensw.co.uk/projects/support-for-decision-makers/annual-survey. Accessed 4th February 2011.

RFA 2008. *The Gallagher review of the indirect effects of biofuels production*. Renewable Fuels Agency (RFA), HMSO, London. Available from: http://www.dft.gov.uk/rfa/_db/_documents/ Report_of_the_Gallagher_review.pdf. Accessed 9th February 2009.

RFA 2011. *Year Two of the RTFO – Renewable Fuels Agency (RFA) report on the Renewable Transport Fuel Obligation 2009/10*. HMSO, London.

Richter, G.M., Riche, A.B., Dailey, A.G., Gezan, S.A., Powlson, D.S., 2008. Is UK fuel supply from Miscanthus water-limited? *Soil Use and Management*, vol. **24**, pp. 235-245.

Roberts, F. 1978. "The aims, methods and uses of energy accounting", *Applied Energy*, vol. **4**, pp. 199-217.

Rosillo-Calle, F., de Groot, P., Hemstock, S. L. & Woods, J.L. 2007. *The Biomass Assessment Handbook*, Earthscan, London.

Rowe, R. L., Street, N. R., & Taylor, G. 2009. "Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK", *Renewable and Sustainable Energy Reviews*, vol. **13**, pp. 271-290.

Royal Society, 2008. *Sustainable biofuels: prospects and challenges*. The Royal Society, London.

Sage, R.B., 1998. "Short rotation coppice for energy: towards ecological guidelines", Biomass & Bioenergy, vol. **15,** pp. 39–47.

Sage, R.B., Cunningham, M. and Boatman, N., 2006. "Birds in willow short-rotation coppice compared to other arable crops in central England and a review of bird census data from energy crops in the UK", *IBIS*, vol. **148**, special issue 1, pp. 184–197.

Scholes, H. 1998. "Can energy crops become a realistic CO_2 mitigation option in South West England?", *Biomass & Bioenergy*, vol. **15**, pp. 333-344.

Semere, T. & Slater, F. M. 2007. "Ground flora, small mammal and bird species diversity in miscanthus (Miscanthus x giganteus) and reed canary-grass (Phalaris arundinacea) fields", *Biomass & Bioenergy*, vol. **31**, pp. 20-29.

SFOE 1998. *Gas Cleaning and Waste Water Treatment for Small Scale Biomass Gasifiers*. Swiss Federal Office of Energy (SFOE), Zurich, Switzerland.

Sherrington, C., Bartley, J., & Moran, D. 2008. "Farm-level constraints on the domestic supply of perennial energy crops in the UK", *Energy Policy*, vol. **36**, pp. 2504-2512.

Slesser, M. 1978. *Energy in the Economy*. Macmillan Press, London.

Slesser, M. 1988. *Macmillan Dictionary of Energy*. Macmillan Press, London.

Slesser, M. & Lewis, C. 1979. *Biological energy resources*, 1st ed, E. & F.N. Spon Ltd, London.

Smeets, E. M. W., Faaij, A. P. C., Lewandowski, I. M., & Turkenburg, W. C. 2007. "A bottom-up assessment and review of global bio-energy potentials to 2050", *Progress in Energy and Combustion Science*, vol. **33**, pp. 56-106.

Smeets, E. M. W., Lewandowski, I. M., & Faaij, A. P. C. 2009. "The economical and environmental performance of miscanthus and switchgrass production and supply chains in a European setting", *Renewable and Sustainable Energy Reviews*, vol. **13**, pp. 1230-1245.

Smith, K. A., Charles, D. R., & Moorhouse, D. 2000. "Nitrogen excretion by farm livestock with respect to land spreading requirements and controlling nitrogen losses to ground and surface waters. Part 2: pigs and poultry", *Bioresource Technology*, vol. **71**, pp. 183-194.

Smith, K. A. & Frost, J. P. 2000. "Nitrogen excretion by farm livestock with respect to land spreading requirements and controlling nitrogen losses to ground and surface waters. Part 1: cattle and sheep", *Bioresource Technology*, vol. **71**, pp. 173-181.

Soffe, R. (ed.) 2003. *The Agricultural Notebook. 20th Edition*. Blackwell Science, Oxford.

South West Regional Assembly 2004. *From Rubbish to Resource – The Regional Waste Strategy for the South West 2004 – 2020.* South West Regional Assembly, Somerset.

Sovacool, B.K. 2008. "Valuing the greenhouse gas emissions from nuclear power: A critical survey", *Energy Policy*, vol. **36**, pp. 2950-2963.

SSEW 1984. *Soils and their use in South West England*. Bulletin 14, Lawes Agricultural Trust Soil Survey of England and Wales (SSEW), Rothamsted, Harpenden.

St. Clair, S., Hillier, J., & Smith, P. 2008. "Estimating the pre-harvest greenhouse gas costs of energy crop production". *Biomass & Bioenergy*, vol. **32**, pp. 442-452.

Styles, D. & Jones, M. B. 2007. "Energy crops in Ireland: Quantifying the potential life-cycle greenhouse gas reductions of energy-crop electricity", *Biomass & Bioenergy*, vol. **31**, pp. 759-772.

Supergen 2008. *"Theme 6 Resource Assessment & Feedstock Properties"*, Supergen Biomass and Bioenergy Consortium, University of Manchester and King's College London.

Swiss Centre for Life Cycle Inventories 2009. *Ecoinvent database [v2.0].* EPMA, Switzerland.

SWO 2010. *State of the South West* [online]. South West Observatory (SWO). Available from: http://www.swo.org.uk/publications/. Accessed 19th October 2010.

Tampier, M., Smith, D., Bibeau, E. & Beauchemin, P. 2004. *Identifying Environmentally Preferable Uses for Biomass Resources.* Stage 2 report: life-cycle GHG emission reduction benefits of selected feedstock-to-product threads, Natural Resources Canada, North Vancouver, Canada.

TA Luft. 2002. *Technical Instructions on Air Quality Control.* Federal Ministry for Environment, Nature Conservation and Nuclear Safety, Germany. Available from: http://www.bmu.de/english/air_pollution_control/ta_luft/doc/36958.php. Accessed 4th April 2010.

Thornley, P. 2008. "Airborne emissions from biomass based power generation systems", Environmental Research Letters, vol. **3,** pp. 1-6**.**

Thornley, P. & Cooper, D. 2008. "The effectiveness of policy instruments in promoting bioenergy", *Biomass & Bioenergy*, vol. **32**, pp. 903-913.

Thornley, P., Rogers, J., & Huang, Y. 2008. "Quantification of employment from biomass power plants", *Renewable Energy*, vol. **33**, pp. 1922-1927.

Thornley, P., Upham, P., Huang, Y., Rezvani, S., Brammer, J., & Rogers, J. 2009a. "Integrated assessment of bioelectricity technology options", *Energy Policy*, vol. **37**, pp. 890-903.

Thornley, P., Upham, P., & Tomei, J. 2009b. "Sustainability constraints on UK bioenergy development", *Energy Policy*, vol. **37**, pp. 5623-5635.

Tuck, G., Glendining, M. J., Smith, P., House, J. I., & Wattenbach, M. 2006. "The potential distribution of bioenergy crops in Europe under present and future climate", *Biomass & Bioenergy*, vol. **30**, pp. 183-197.

Udo de Haes, H. A. & Heijungs, R. 2007. "Life-cycle assessment for energy analysis and management", *Applied Energy*, vol. **84**, pp. 817-827.

UK Parliament 2008a. *Climate Change Act (chapter 27)* [online]. HMSO, London. Available from: http://www.opsi.gov.uk/acts/acts2008/pdf/ukpga_20080027_en.pdfS. Accessed 4th March 2010.

UK Parliament 2008b. *Energy Act (chapter 32)* [online]. HMSO, London. Available from: http://www.opsi.gov.uk/acts/acts2008/pdf/ukpga_20080032_en.pdfS. Accessed 4th March 2010.

UKERC 2010. *The UK bio-energy resource base to 2050: estimates, assumptions, and uncertainties.* UK Energy Research Centre (UKERC), Imperial Centre for Energy Policy and Technology, London.

Upham, P. & Shackley, S. 2007. "Local public opinion of a proposed 21.5MW(e) biomass gasifier in Devon: Questionnaire survey results", *Biomass & Bioenergy*, vol. **31**, pp. 433-441.

Upham, P. & Shackley, S. 2006. "The case of a proposed 21.5MW(e) biomass gasifier in Winkleigh, Devon: Implications for governance of renewable energy planning", *Energy Policy*, vol. **34**, pp. 2161-2172.

Upreti, B. R. 2004. "Conflict over biomass energy development in the United Kingdom: some observations and lessons from England and Wales", *Energy Policy*, vol. **32**, pp. 785-800.

van der Horst, D. 2007. "NIMBY or not? Exploring the relevance of location and the politics of voiced opinions in renewable energy siting controversies", *Energy Policy*, vol. **35**, pp. 2705-2714.

Venturi, P., Gigler, J. K., & Huisman, W. 1999. "Economical and technical comparison between herbaceous (Miscanthus x giganteus) and woody energy crops (Salix viminalis)", *Renewable Energy*, vol. **16**, pp. 1023-1026.

Venturi, P. & Venturi, G. 2003. "Analysis of energy comparison for crops in European agricultural systems", *Biomass & Bioenergy*, vol. **25**, pp. 235-255.

Verhoef, E. V., Dijkema P. J. & Markus, A. 2004. "Process Knowledge, System Dynamics, and Metal Ecology", *Industrial Ecology*, MIT press, Vol. **8**, Number 1–2.

von Blottnitz, H. & Curran, M. A. 2007. "A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective", *Journal of Cleaner Production*, vol. **15**, pp. 607-619.

WCED 1987. *Our Common Future*. World Commission on Environment and Development (WCED), Oxford University Press, Oxford.

Wessex Water 2010. *Sustainability Indicators 2010.* Available from: www.wessexwater.co.uk/sustainability. Accessed 19th December 2010.

Woods, J., Tipper, R., Brown, G., Diaz-Chavez, R., Lovell, J. & de Groot, P. 2006. *Evaluating the Sustainability of Co-firing in the UK (Report for the DTI).* Report No. URN 06/1960, Themba Technology Ltd, Department of Trade and Industry, HMSO, London.

World Health Organization, 2003. *Health aspects of air pollution with particulate matter, ozone and nitrogen dioxide.* Report on a WHO working group 13-15 January 2003, Bonn, Germany.

Worldwatch Institute 2007. *Biofuels for Transport – Global potential and iImplications for sustainable energy and agriculture.* ISBN 1-84407-422-6. Earthscan, London.

WRAP, 2009. *Wood waste market in the UK*. Project no. MKN022. Pöyry Forest Industry Consulting Ltd and Oxford Economics Ltd, WRAP, Banbury.

Yeatman, C.O. 2006. *The Profitable use of Anaerobic Digestion (AD) on UK Farms*. A 2005/06 Nuffield Farming Scholarship Study. Available from: http://www.nuffieldinternational.org/rep_pdf/1226661015Yeatman_Owen.pdf. Accessed 21st August 2009.

APPENDIX A. PUBLISHED PAPERS

The following three papers are reproduced in this appendix:

pp. 244-254 Adams, P.W., Hammond, G.P., McManus, M.C. & Mezzullo, W.G. 2011. "Barriers to and drivers for UK bioenergy development", *Renewable and Sustainable Energy Reviews*, Volume **15**, Issue 2, February 2011, pp. 1217-1227

pp. 255-256 Adams, P.W., Hammond, G.P., & McManus M.C. 2009. "Environmental Life Cycle Assessment of a Biomass Gasification CHP Plant", *Society of Environmental Toxicology and Chemistry (SETAC) 19th Life Cycle Assessment Symposium*, pp. 35-36, 1-2 February 2010, Unviversity of Poznan, Poland.

pp. 257-274 Adams, P.W., Hammond, G.P., & McManus M.C. 2010. "Life Cycle Environmental and Energy Appraisal of a Biomass Gasification CHP Plant", *Bioten conference proceedings, In press*, 21-23 September 2010, Birmingham.

APPENDIX B. BIOMASS & BIOENERGY SUPPORTING INFORMATION

BIOMASS FEEDSTOCK COMPOSITION

In Chapter 2 the elemental composition of different biomass types are discussed. Table B-1 gives the ultimate analyses for some biomass materials on a dry and ash free basis.

Table B-1: Ultimate analyses for typical biomass materials and solid fossil fuels – dry and ash free basis (wt%) (Vassilev et al., 2010)

Material	C	H	O	N	S
Wheat straw	49.4	6.1	43.6	0.7	0.17
Miscanthus	49.2	6.0	44.2	0.4	0.15
Willow	49.8	6.1	43.4	0.6	0.06
Wood (average)	52.1	6.2	41.2	0.4	0.08
Wood waste	52.2	7.3	40.4	1.1	0.30
Sewage sludge	50.9	7.3	33.4	6.1	2.33
Coal	78.2	5.2	13.6	1.3	1.7
Lignite	64.0	5.5	23.7	1.0	5.8

Fuel analysis has been developed based on solid fuels, such as coal, which consists of chemical energy stored in two forms, fixed carbon and volatiles (McKendry, 2002a). The proximate analysis of a fuel is determined using laboratory tests and is based upon the volatile matter, ash and water content, with the fixed carbon determined by the difference (ECN, 2009). Table B-2 displays some examples of proximate analysis for a sample of biomass feedstocks. It is important to note that the exact composition of an individual species will vary depending on the environment in which it was grown, for example soil composition, rainfall, sunlight, etc. Therefore different samples of the same species will have some variability.

Table B-2: Proximate analysis of some biomass feedstocks (wt%) (Vassilev et al., 2010)

Biomass	Volatile matter (%)	Fixed carbon (%)	Moisture content (%)	Ash (%)	LHV (MJ/kg)
Wheat straw	67.2	16.3	10.1	6.4	17.3
Miscanthus	71.9	14.0	11.4	2.7	17.3
Willow	74.2	14.3	10.1	1.4	18.3
Wood (average)	77.5	14.5	7.8	0.2	18.6
Wood waste	72.9	11.8	12.1	3.2	18.5
Coal	57.8	24.3	14.6	3.3	34.0
Lignite	32.8	25.7	10.5	31.0	26.8

GASIFICATION TECHNOLOGIES

Although some suppliers claim to be able to gasify all types of fuels, in practice it has become apparent that multi-fuel gasifiers do not exist due to the versatility of biomass resources (Knoef, 2005). For instance, biomass can be wet or dry, small or large, dense or light, high or low ash content, homogeneous or non-homogeneous, etc. This makes the use of the full range of biomass fuels in dedicated gasifier reactors less economically viable, and in most cases some pre-treatment of the biomass is needed (IEE, 2007). The type of pre-treatment depends on the biomass characteristics; it's physical and chemical composition (see Chapter 2). Each type of biomass has its own specific properties which determine its performance as a fuel in gasification plants. This has led to many different designs of gasifier being developed. Each gasification technology varies depending on how the biomass is fed into the gasifier and is moved around within it. Biomass is either fed into the top of the gasifier, or into the side, and then is moved around either by gravity or air flows. Other variables include:

- Whether oxygen, air or steam is used as an oxidant – using air dilutes the syngas with nitrogen, which adds to the cost of downstream processing. Using oxygen avoids this, but is expensive, and so oxygen enriched air can also be used;
- The temperature range in which the gasifier is operated;
- Whether the heat for the gasifier is provided by partially combusting some of the biomass in the gasifier (directly heated), or from an external source (indirectly heated), such as circulation of an inert material or steam;
- Whether or not the gasifier is operated at above atmospheric pressure.

Entrained Flow Gasification

The biomass gasification system developed by Sustainable Energy Ltd was an entrained flow gasifier. The entrained flow gasifier uses air to entrain wood powder (in the form of sawdust) in a turbulent vortex within the reactor, which incorporates two stages of separation to remove the char and ash produced in the process. The intense continuous reaction enables gasification of high volumes of biomass in the compact reactor.

CHP ENGINES

Anaerobic Digestion (AD) is a much more established technology than gasification. As such, biogas plants across Europe are a good indicator of the type of engines which are utilised. Approximately 50% of CHP systems installed in Europe run with four-stroke engines and about 50% with ignition diesel engines (Deublein & Steinhauser, 2008). More modern technologies like micro gas turbines and fuel cells are not very common (Ecofys, 2005). The total efficiency, i.e. the sum of electrical and thermal efficiencies, can be up to 90% with modern CHP systems (Carbon Trust, 2010). In comparison, electrical efficiencies are up to about 40%, which is why making use of the heat is so beneficial.

Four-stroke engines used today were originally developed for natural gas and consequently are well adapted to the special features of producer gas or biogas (Deublein & Steinhauser, 2008; Knoef, 2005). Nitrogen oxide output NO_x has to be kept below prescribed values which means electrical efficiency does not exceed 40% (Lieuwen *et al.*, 2010). Capacities of four-stroke gas engines and diesel engines typically range between 100 kW and 1 MW and have a lifetime circa 60,000 hours (Deublein & Steinhauser, 2008). An overview of the different technologies with some characteristic performance data is given in Table B-3.

Table B-3: Characteristic values of CHP technologies (source: Deublein & Steinhauser, 2008)

Feature	Four-stroke engine	Gas-Diesel engine	Ignition oil Diesel engine	Stirling engine	Fuel cell	Gas turbine	Micro gas turbine
Range of capacity (kWe)	<100	>150	30-1000	<150	1-10000		30-110
Electrical efficiency	30-40%	35-40%	32-40%	30-40%	40-70%	25-35%	15-33%
Cooling water temperature	110°C	110°C	110°C	60°C	n/a	210°C	300-500°C
Emissions NOx	High	High	600- 700 mg/Nm^3	Very low	Very low 3 mg/Nm^3	Low 25 mg/Nm^3	Low 20 mg/Nm^3
Alternative fuel in case of shortage	Liquid gas	Liquid gas	Petrol, vegetable oil	Any	Natural gas	Natural gas	Natural gas, kerosene, fuel oil

A four-stroke engine typically operates at about 1500 rpm and consists of: an engine block with crankshaft; crankshaft bearings and seals; engine housing; piston rod; piston with piston rings; cylinder; oil sump; flywheel housing; cylinder head with cylinder head gasket; cam shaft; valves; tappet; rocker arm.

APPENDIX C. LIFE CYCLE IMPACT ASSESSMENT SUPPORTING INFORMATION

LCA SOFTWARE REVIEW

Table C-1: Main software packages reviewed for this research

Software Name	Link
Boustead Model	http://www.boustead-consulting.co.uk/products.htm/
CMLCA	http://www.cmlca.eu/
GaBi 4 Software	http://www.gabi-software.com/software/gabi-4/
GEMIS	http://www.oeko.de/service/gemis/en/index.htm/
GREET	http://greet.es.anl.gov/
IDEMAT	http://www.idemat.nl/
Open LCA	http://www.openlca.org/index.html/
SimaPro	http://www.pre.nl/simapro/default.htm/
TEAM	https://www.ecobilan.com/uk_team.php/

The information includes a web-link so the reader can further research each software option. SimaPro was selected as preferable to the other software options because it was the most flexible in the way in which the data could be analysed and interpreted. It includes the largest number of inventory databases and impact assessment methods, and it is also well integrated with the Ecoinvent LCI database. At the SETAC Europe 16th LCA Case Studies Symposium attended by the author in January 2010 a review of the 32 case studies presented showed that over 40% of authors used SimaPro and around 30% used GaBi. This provides some additional confirmation that SimaPro is widely used throughout the LCA research community.

IMPACT ASSESSMENT METHODOLOGY REVIEW

Table C-2: Life cycle impact assessment methodologies reviewed for this research

LCIAM Name	Background publication
CML 2001	(Guinée et al., 2002)
Cumulative Energy Demand (CED)	(Frischknecht et al., 2007)
Cumulative Exergy Demand (CExD)	(Frischknecht et al., 2007)
Eco-indicator 99	(Goedkoop et al., 2000)
Ecological footprint	(Frischknecht et al., 2007)
Ecological scarcity	(Brand *et al.*, 1998)
Ecosystem damage potential (EDP)	(Koellner & Scholz, 2007)
EDIP 2003 – Environmental Design of Industrial Products	(Hauschild & Potting J., 2004)
EPS 2000 – Environmental priority strategies in product development	(Steen, 1999)
IMPACT 2000+	(Jolliet *et al.*, 2003)
IPCC 2001 (Climate Change)	(Frischknecht et al., 2007)
ReCiPe	(Goedkoop et al., 2009)
TRACI - The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts	(Bare *et al.*, 2002)

CML and **Eco-Indicator 99** were found to be the most commonly used LCIAMs, and had the most comprehensive characterisation factors. Eco-indicator 99 was selected as the LCIAM used initially in the case studies. CML does not include land-use or particulate matter formation, which were both considered to be critical when assessing bioenergy systems. Therefore CML was excluded from consideration despite being one of the most widely used midpoint LCIAM. **ReCiPe** is a relatively new impact assessment methodology which became available during the research. ReCiPe combines both CML and Eco-Indicator 99 and provides more up to date characterisation factors.

CED and **CExD** were considered most appropriate for net energy (& exergy) analysis as they do not assess other environmental impacts. CED is therefore utilised in the net energy analysis studies. **Ecological footprint** was thought to be too narrow a LCIAM as it is concerned primarily with land use and does not consider other impacts. **Ecological scarcity** contains characterisation factors for different emissions to air, water and top-soil/ground-water as well as for the use of energy resources and some types of waste. This method allows a comparative weighting and aggregation of various environmental interventions by use of so-called eco-factors (Brand *et al.*, 1998). Ecological scarcity had good potential but was excluded because Eco-Indicator 99 had more and better defined impact categories. It was also excluded because it was largely based on Swiss data, included subjective weighting and was not as up to date as Eco-Indicator 99.

EDP only assesses the characterisation of land occupation and transformation so was excluded as being too narrow. **EDIP** is a thoroughly documented midpoint approach covering most of the emission-related impacts, resource use and working environment impacts (Hauschild & Potting J., 2004) with normalisation based on person equivalents. EDIP is comparable to CML but includes more impact categories and has quite different characterisation factors for the chemical impacts on human health and ecosystem health (Dreyer *et al.*, 2003). EDIP does not differentiate between fossil fuel and mineral resource depletion and does not include land use, so was not considered appropriate for this study.

EPS 2000 includes a number of impact categories but sometimes in a course manner (Pre Consultants, 2008). Characterisation factors are mainly taken for global conditions in 1990 and represent average emission rates. EPS 2000 was excluded since it was not as up to date as Eco-Indicator 99 and also excluded land-use. **IMPACT 2000+** was a promising LCIAM as it produces results at both the midpoint and endpoint. However, the characterisation factors are based on CML (midpoint) and Eco-indicator 99. Therefore it was considered more appropriate to use either ReCiPe or the original LCIAM, as their characterisation and normalisation factors are more up to date.

IPCC 2001 is a method developed by the International Panel on Climate Change (IPCC). This method lists the climate change factors of IPCC with a timeframe of 20, 100 and 500 years. This LCIAM was not appropriate as only climate change is considered. **ReCiPe** was selected for use in this study. **TRACI** is a midpoint orientated LCIAM which has similar impact categories to Eco-indicator 99. It is US-based and consequently has characterisation factors based on the USA. TRACI was not used because of this and also the depletion characterisation models are not implemented in SimaPro.

APPENDIX D. LIST OF BIOENERGY PLANTS IDENTIFIED IN THE SOUTH WEST

Table D-1: List of renewable electricity installations

Generating Station	Capacity (kW)	Organisation	Address
Advanced treatment of waste			
Compact Power Avonmouth Plant	225	Compact Power Limited	Avonmouth Refuse Transfer Station, BS11 0YS
Holsworthy Biogas Company	2696	Andigestion	Higher Mansworthy, Holsworthy EX22 7HH
Lowbrook dairy farm	365	Farmergy Ltd	Lower Belchallwell, Blandford, DT11 0EQ
Smerrill dairy	300	Kemble Farms Ltd	Smerrill, Kemble, Cirencester, GL7 6BN
Landfill gas sites			
Broadpath Power Plant	4890	Viridor Waste Disposal Ltd	Uffculme, Devon, EX15 3EP
Calne Landfill	3500	Viridor Waste Disposal Ltd	Sand Pit Road, Calne, SN11 8TF
Compton Bassett Landfill	2346	Novera Energy Generation Ltd	Old Camp Farm, Compton Bassett, Nr Calne, Wiltshire, SN11 8RB
Connon Bridge 2 Landfill Gas - A	4260	CLP Envirogas Limited	East Taphouse, Liskeard, Cornwall, PL14 4NP
Connon Bridge 2 Landfill Gas - B	1006	CLP Envirogas Limited	
Deep Moor Gas to Energy	2006	Infinis (Re-Gen) Limited	Deep Moor Landfill, High Bullen, Nr Torrington, Devon, EX38 7JA
Dimmer Landfill Gas Generation	2500	Gengas Ltd	Dimmer, Nr Castle Cary, Somerset
Dimmer Landfill Site	2006	Gengas Ltd	
Harn Hill Quarry	2684	Viridis Energy (Norgen) Ltd	Aust Road, Olvaston, Nr Bristol
Hempsted Landfill	8242	Infinis (Re-Gen) Limited	Hempsted Lane, Gloucester, Gloucestershire
Odcombe Landfill	660	Gengas Ltd	Street Lane, OdcombeYeovil, Somerset, BA22 8UP
Walpole Landfill	1740	Infinis (Re-Gen) Limited	Pawlett, Bridgwater, Somerset, TA6 4TF
Walpole Landfill Phase 2 - A,C	825	Infinis (Re-Gen) Limited	
Westbury Power Plant	1189	Viridor Waste Disposal Ltd	Trowbridge Road, Westbury, Wiltshire
Wingmoor Landfill (Infinis)	2809	Infinis (Re-Gen) Limited	Stoke Orchard, Nr Bishop Cleeve, Cheltenham, GL52 4RY
Yanley	1561	Viridor Waste Disposal Ltd	Bridgewater Road, Bristol, England
Yanley Phase II	580	Viridor Waste Disposal Ltd	
Poole generation plant	1035	EDL (UK) LFG Generation Ltd	Poole Landfill Site, Poole, Wellington, Somerset, TA21 9HH
Westbury Phase II	2100	Viridor Waste Disposal Ltd	Towbridge Road, Westbury, Wiltshire
Heathfield "C" Power Plant	2378	Viridor Waste Disposal Ltd	John Acres Lane, Fosterville Newton Abbott, Devon, TQ12 3GP
Heathfield "A" Power Plant	6141	Viridor Waste Disposal Ltd	
Sewage gas sites			
Berryhill STW	900	Wessex Water Services Ltd	Watery Lane, Bournemouth, Dorset, BH8 0AJ
Countess Wear STW	660	South West Water Ltd	Bridge Road, Countess Wear, Exeter, Devon, EX2 7AA
Kilmington STW CHP A	105	South West Water Ltd	Axminster, Devon, EX13 7RG
Kilmington STW CHP B	105	South West Water Ltd	
Kingsbridge STW CHP	60	South West Water Ltd	Gerston Lane, Kingsbridge, TQ7 3AZ
Liskeard STW CHP	60	South West Water Ltd	Lodge Hill, Liskeard, Cornwall, PL14 4JP
Plympton STW CHP	270	South West Water Ltd	Marshall Road, Plympton, Devon, PL7 1YB
Poole STW CHP	1395	Wessex Water Services Ltd	Cabot Lane, Poole, Dorset, BH17 7LG
Swindon STW	450	Thames Water Utilities Ltd	Barnfield Road, Swindon, Wiltshire, SN2 2DP
Salisbury STW CHP	85	Wessex Water Services Ltd	Petersfinger, Southampton Road, Salisbury, SP5 3EU
Taunton STW CHP	170	Wessex Water Services Ltd	Ham Lane, Creech St Michael, Taunton, TA3 5NU
Totnes STW CHP	105	South West Water Ltd	Newton Road, Totnes, Devon, TQ9 5XN
Trowbridge STW	85	Wessex Water Services Ltd	Bradford Road, Trowbridge, Wiltshire, BA14 8NX
Stroud STW	240	Severn Trent Water Ltd	Leonards Stanley, Stonehouse, Gloucestershire, GL10 3QX
Nanstallon STW	105	South West Water Ltd	Stony Lane, Bodmin, PL31 2QX
Netheridge 2 STW	836	Severn Trent Water Ltd	Hempstead Lane, Hempstead, Gloucester, GL2 5LF

Key: STW = Sewage treatment works

Table D-2: List of renewable heat installations

Project name	Building Type	Capacity (kW)	Estimated woodchip (Odt/yr)	Source	County
Kernock Plants	Commercial greenhouse	3000	3,000	Wood Energy	Cornwall
Treco - Devon	Commercial	1440	630	Treco	Devon
Jackson Plants	Commercial greenhouse	1200	1,200	RE4D	Devon
Guys Marsh Prison II	Public - Other	1200	525	Wood Energy Ltd	Dorset
Crofters, Trelissick	Charity (Community)	970	473	National Trust	Cornwall
Devon County Council	Public - LA	850	372	EST / DECC	Devon
National Star College	School	820	272	Econergy	Gloucestershire
Treco - Dorset	Commercial	780	341	Treco	Dorset
Royal Cornwall Hospital	Public - NHS	750	328	Econergy	Cornwall
BSF Brislington Enterprise College	School	650	216	Wood Energy Ltd	Former Avon
BSF Hartcliffe Skanska	School	600	199	Wood Energy Ltd	Former Avon
Lanoyce Nurseries	Commercial greenhouse	500	500	Wood Energy Ltd	Cornwall
Bideford College	School	500	166	Wood Energy Ltd	Devon
RMB Poole	Commercial	500	219	Wood Energy Ltd	Dorset
Bristol Museum	Public - LA	500	219	Wood Energy Ltd	Former Avon
The Park Community Centre	School	500	166	Bristol City Council	Former Avon
Archway School	School	500	166	SWEA	Gloucestershire
Bath and West Showground	Commercial	500	219	Wood Energy Ltd	Somerset
Castle Drogo	Charity (Community)	400	150	Wood Energy Ltd	Devon
Blaise Nursery	Public - LA	400	175	Wood Energy Ltd	Former Avon
BSF - Speedwell / Brunel	School	400	133	Wood Energy Ltd	Former Avon
South Gloucestershire Council Offices	Public - LA	400	175	South Gloucestershire Council	Former Avon
Cotswold Chine School	School	400	133	SWEA	Gloucestershire
Whitefield Fishponds Community School BSF Skanska	School	360	119	Wood Energy Ltd	Former Avon
Tiverton	Commercial	350	153	Wood Energy Ltd	Devon
Marsden Farms	Commercial	330	144	Econergy	Gloucestershire
Rednock School	School	320	106	Econergy	Gloucestershire
Bowood House	Commercial	320	140	Econergy	Wiltshire
Swindon Academy	School	320	106	Econergy	Wiltshire
Old County Hall	Public - LA	300	131	energy-crops	Cornwall
Pencalenick School	School	300	100	Wood Energy Ltd	Cornwall
Trelowarren Estate	Commercial	300	131	churton-inge.co.uk	Cornwall
Eden Project	Commercial	300	131	Wood Energy Ltd	Cornwall
Kings Park Nursery	School	300	100	Bournemouth Borough Council	Dorset
Winford Manor	Commercial	300	131	Wood Energy Ltd	Former Avon
Batsford Estate	Commercial	300	131	SWEA	Gloucestershire
Treco - Somerset	Commercial	300	131	Treco	Somerset
Treco - Wiltshire	Commercial	280	123	Treco	Wiltshire
Loyton Lodge	Commercial	250	109	Wood Energy Ltd	Devon
SME	Commercial	250	109	confidential	Devon
Treco - Gloucs	Commercial	240	105	Treco	Gloucestershire
LCBP Stream 1	Domestic	238	71	EST / DECC	Somerset
Florence Brown School	School	230	76	CSE	Former Avon
Kings Forest Primary School	School	230	76	Wood Energy Ltd	Former Avon
Penryn College	School	220	73	Econergy	Cornwall
Camelford Primary School	School	220	73	Econergy	Cornwall
Launceston	School	220	73	Wood Energy Ltd	Cornwall
Residential Building / Commercial Building?	Domestic	220	66	Wood Energy Ltd	Devon
Withington Estate	Commercial	220	96	Econergy	Gloucestershire
Residential Building	Domestic	220	66	Wood Energy Ltd	Somerset

Project name	Building Type	Capacity (kW)	Estimated woodchip (Odt/yr)	Source	County
Sharpham Trust	Commercial	200	88	sharpham-trust	Devon
Abbotswood Primary School	School	200	66	South Gloucestershire Council	Former Avon
Filton Hill Primary School	School	200	66	South Gloucestershire Council	Former Avon
Stoke Lodge Primary	School	200	66	South Gloucestershire Council	Former Avon
LCBP Stream 1	Domestic	186	56	EST / DECC	Devon
Residential Building	Domestic	185	56	Wood Energy Ltd	Somerset
LCBP Stream 1	Domestic	160	48	EST / DECC	Cornwall
Treco - Former Avon	Commercial	160	70	Treco	Former Avon
Tregothnan Estate	Commercial	150	66	Wood Energy	Cornwall
Westerhope Units	Commercial	150	66	Wood Energy Ltd	Devon
Residential Building	Domestic	150	45	Wood Energy Ltd	Devon
Bettridge School	School	150	50	Econergy	Dorset
Guys Marsh Prison I	Public - Other	150	66	Dorset County Council	Dorset
Folly Farm Environment Centre	Commercial	150	73	CSE	Former Avon
Netham Recreation Ground, Pavillion	Public - LA	150	66	CSE	Former Avon
Gillingstool School	School	150	50	Econergy	Former Avon
Residential Building	Domestic	149	45	Wood Energy Ltd	Devon
Bovington Camp	Commercial	149	65	Wood Energy Ltd	Dorset
LCBP Stream 1	Domestic	132.3	40	EST / DECC	Devon
LCBP Stream 1	Domestic	132	40	EST / DECC	Somerset
LCBP Stream 1	Domestic	118	35	EST / DECC	Somerset
Residential Building	Domestic	117	35	Wood Energy	Devon
Nethercott House	Community	117	57	Wood Energy Ltd	Devon
Residential Building	Domestic	117	88	Wood Energy Ltd	Devon
Winkleigh Farms Biomass Boiler	Commercial	117	51	Winkleigh Farms for City Children	Devon
LCBP Stream 1	Domestic	111	33	EST / DECC	Former Avon
Residential Building	Domestic	110	33	Econergy	Devon
Wilderness Centre	Commercial	110	48	Econergy	Gloucestershire
Residential Building	Domestic	110	33	Econergy	Somerset
Residential Building	Domestic	110	33	Econergy	Somerset
Eastcourt House	Commercial	110	48	Econergy	Wiltshire
LCBP Stream 1	Domestic	103	31	EST / DECC	Devon
Residential Building	Domestic	100	30	CSEP	Cornwall
Belle Isle Nursery	Commercial	100	44	Econergy	Devon
Mornacott Farms	Commercial	100	44	Treco	Devon
Residential Building	Domestic	100	30	confidential	Devon
Residential Building	Domestic	100	30	RE4D	Devon
West Buckland School	School	100	33	Econergy	Devon
Slapton Ley Field Centre	Community	100	73	CSE	Devon
Paignton Crocodile Swamp	Commercial	100	44	Econergy	Devon
Residential Building	Domestic	100	30	Wood Energy Ltd	Devon
Poundbury	Commercial	100	44	Econergy	Dorset
Trinity Primary School	School	100	33	SWEA	Former Avon
Residential Building	Domestic	100	30	Dunster Wood Fuels Ltd	Somerset
Residential Building	Domestic	100	30	Wood Energy Ltd	Somerset
Residential Building	Domestic	100	30	Wood Energy Ltd	Somerset
Residential Building	Domestic	100	30	Wood Energy Ltd	Somerset
Stanton St Quintin	School	100	33	Ashwell Engineering	Wiltshire
LCBP Stream 1	Domestic	99	30	EST / DECC	Devon
Jubilee Wharf	Commercial	93	41	Wood Energy	Cornwall

Project name	Building Type	Capacity (kW)	Estimated woodchip (Odt/yr)	Source	County
Bampton Primary School	School	93	31	Wood Energy Ltd	Devon
Public Building	Public - Other	90	39	SWEA	Gloucestershire
Sherwood House	Commercial	85	37	Econergy	Devon
Daylesford Estate	Commercial	80	35	Econergy	Gloucestershire
Dunkeswell Eco Business Park	Commercial	75	55	CSE	Devon
Residential Building	Domestic	75	23	Cliff carter - 07811 376097 - cliffcarter@cobworthy.co.uk	Devon
Residential Building	Domestic	75	23	Wood Energy Ltd	Somerset
Residential Building	Domestic	75	23	Dunster Wood Fuels Ltd	Somerset
West Somerset Council Office	Public - LA	75	33	westsomerset.gov.uk	Somerset
Pinkworthy Barn	Commercial	70	31	Wood Energy Ltd	Devon
Residential Building	Domestic	70	21	Wood Energy Ltd	Devon
Kingston Maurward College	School	70	44	Coordinated Woodfuel Initiative managed by CSE.	Dorset
Magdalen Project	Community	70	34	Dorset County Council	Dorset
Ebworth Centre	Commercial	70	31	Econergy	Gloucestershire
Fernhill Farm	Commercial	70	40	Econergy	Somerset
Residential Building	Domestic	70	40	CSE	Somerset
Residential Building	Domestic	70	55	CSE	Wiltshire
LCBP Stream 1	Domestic	67	20	EST / DECC	Gloucestershire
LCBP Stream 1	Domestic	62	19	EST / DECC	Somerset
Beech Hill Community	Community	60	29	DARE	Devon
Commercial Building	Commercial	60	26	Eco Exmoor	Devon
Charles Moore	Commercial	60	26	RE4D	Devon
Residential Building	Domestic	60	18	Coordinated Woodfuel Initiative managed by CSE.	Somerset
NMSI Engineering Building	Public - Other	60	26	Econergy	Wiltshire
Torhill Farm	Commercial	55	24	RE4D	Devon
Kingcombe Trust, The	Community	55	31	CSE	Dorset
Goblin Combe	Commercial	55	24	Econergy	Former Avon
Residential Building	Domestic	55	17	Econergy	Wiltshire
LCBP Stream 1	Domestic	51	15	EST / DECC	Somerset
Lower Thurlibeer	Commercial	50	22	Wood Energy Ltd	Cornwall
Residential Building	Domestic	50	15	Wood Energy Ltd	Cornwall
Trenance Downs sawmill	Commercial	50	22	Wood Energy Ltd	Cornwall
Bicton Arena	Commercial	50	22	Wood Energy Ltd	Devon
Residential Building	Domestic	50	29	Econergy	Devon
Residential Building	Domestic	50	29	CSE	Devon
Residential Building	Domestic	50	15	Wood Energy	Devon
Rolle Estate Offices	Commercial	50	31	Clinton Devon Estates	Devon
Calvin Consulting	Commercial	50	22	Calvin Consulting	Devon
Howard Primary School	School	50	17	Treco	Devon
SME	Commercial	50	22	confidential	Devon
Residential Building	Domestic	50	15	Wood Energy Ltd	Devon
Caddsdown Business Park	Public - LA	50	22	Torridge District Council	Devon
Residential Building	Domestic	50	15	confidential	Devon
Residential building	Domestic	50	15	Treco	Devon
Lynch Lane Nursery	Public -LA	50	22	Dorset County Council	Dorset
Charterhouse Outdoor Centre	Public - LA	50	22	Econergy	Somerset
Otterhampton Primary School	School	50	17	Wood Energy Ltd	Somerset
Residential Building	Domestic	50	15	Econergy	Somerset
Residential Building	Domestic	50	15	Wood Energy Ltd	Somerset
Residential Building	Domestic	50	15	Wood Energy Ltd	Wiltshire

APPENDIX E. PERENNIAL ENERGY CROPS SUPPORTING LIFE CYCLE INVENTORY DATA

In the LCA study performed on the production of perennial energy crops numerous data were used and produced. It was not possible to include all of this in Chapter 6 and therefore some extra detail is provided here in. This appendix presents some additional data from the life cycle inventory (LCI).

DIRECT FIELD EMISSIONS

The following sub-sections, for calculating emissions data from using fertilisers, have been adapted from (Nemecek & Kagi, 2007). The methodologies have been applied to the case studies in order to model emissions from the application of mineral fertilisers.

Emissions of Ammonia to Air

Ammonium (NH_4) contained in fertilisers can easily be converted into ammonia (NH_3) and released to the air (Harrison, 1999). Agriculture accounts for almost 90% of ammonia emissions in the UK (DEFRA, 2009). Ammonia contributes to acidification and the eutrophication of sensitive ecosystems (Goedkoop *et al.*, 2009). Although the impact of emissions of Ammonia to the air is mainly local and regional, it is included in both Eco-Indicator 99 and ReCiPe. Emission factors used in the study for mineral fertilisers given by (Asman, 1992) are shown in Table E-1:

Table E-1: Emission factors of ammonia for mineral fertilisers (source: Asman, 1992)

Type of fertiliser	Emission factor for NH_3-N
Ammonium nitrate, calcium ammonium nitrate	2%
Ammonium sulphate	8%
Multi-nutrient fertilisers (NPK-, NP-, NK-fertilisers)	4%

Nitrate Leaching to Ground Water

Nitrate (NO_3) is either supplied to the soil by fertilisers or produced by micro-organisms in the soil (Harrison, 1999). Nitrate in soil can be absorbed as a nutrient by plants. However, in periods of high rainfall, precipitation exceeds soil evaporation and transpiration of the plants. As nitrate is easily dissolved in water, the risk of nitrate leaching is high.

Nitrate losses are undesirable for several reasons. From the agricultural point of view, valuable nutrients are lost from the soil, increasing the need for fertilisers. Nitrate in ground water used as drinking water may have a toxic impact to humans (Goedkoop *et al.*, 2009). Once ground water becomes surface water, nitrate contributes to eutrophication and induces emissions of nitrous oxide, a major greenhouse gas (Nemecek & Kagi, 2007).

Nitrate emissions to ground water can be estimated by simulation models, although this method is very complex and time-consuming and does not always lead to satisfactory results (Nemecek & Kagi, 2007). For Miscanthus, most nitrogen is stored in the roots and rhizomes (DEFRA, 2007). Similarly, once Willow has an established root system nitrate leaching is reported to be negligible (DEFRA, 2002). Given the difficulties associated with modelling and the low likelihood of nitrate leaching for the perennial energy crops, further research into nitrate leaching in ground water is outside the scope of this study. Therefore, nitrate leaching has not been included in the SimaPro model.

Emissions of Phosphorus to Water

Phosphorus (P) is an important plant nutrient and must be supplied to plants in sufficient quantities (Harrison, 1999). A part of the phosphorus is lost to water due to leaching, run-off and soil erosion through water, causing eutrophication, P is a limiting element (Nemecek & Kagi, 2007). Phosphorous can cause the eutrophication of water, hence in ReCiPe the impact category 'freshwater eutrophication' is measured in kg P eq (Goedkoop *et al.*, 2009).

The modelling of phosphorus emissions in Ecoinvent is distinguished between three different kinds of emissions to water (Swiss Centre for Life Cycle Inventories, 2009):

- Leaching of soluble phosphate to ground water;
- Run-off of soluble phosphate to surface water;
- Erosion of soil particles containing phosphorus.

The emission models for the calculation of P emissions takes soil erosion, surface run-off, draining losses, and leaching to ground water into account. The key factors of the model are listed below (Nemecek & Kagi, 2007):

<u>Phosphorus leaching to ground water</u>

P leaching to the ground water was estimated as an average leaching:

$P_{gw} = P_{gwl} * F_{gw}$

P_{gw} = quantity of P leached to ground water (kg/ha)

P_{gwl} = average quantity of P leached to ground water for a land use category (kg/ha), which is 0.07 kg P/ha for arable land and 0.06 kg P/ha for permanent grassland

F_{gw} = correction factor used for fertilisation by slurry, but is not used in this study.

P Run-off to surface waters

Run-off to surface waters was calculated in a similar way to leaching to ground water:

$P_{ro} = P_{rol} * F_{ro}$

P_{ro} = quantity of P lost through run-off to rivers (kg/ha)

P_{rol} = average quantity of P lost through run-off for a land use category (kg/ha), which is 0.175 kg P/ha for open arable land.

F_{ro} = correction factor used for fertilisation by slurry, but is not used in this study.

P emissions through erosion by water to surface waters

Erosion emissions were not included in this study due to insufficient data available for the calculation. However it should be noted that soil erosion by wind can be important in some parts of South West England, particularly coastal areas in Devon & Cornwall, but is not modelled in this study.

Emissions of Nitrous Oxide (N_2O) to Air

Nitrous oxide is produced as an intermediate product in the denitrification process (conversion of NO_3 into N_2) by soil micro-organisms (Harrison, 1999). It can also be produced as by-product in the nitrification process (Harrison, 1999). Agriculture is the largest source of nitrous oxide emissions in the UK. Around two thirds of N_2O emissions are produced by agriculture, and around 92% of this is from soils, particularly as a result of fertiliser application and leaching.

Calculations of N_2O emissions are based on the IPCC method (IPPC, 1996). Direct emissions of N_2O and indirect or induced emissions are included. N_2O emissions (kg N_2O) from mineral fertilisers are calculated on the basis of the available Nitrogen (kg N). The factor of 1.25% lost as N_2O is used. For mineral fertilisers, it is assumed that 100% of the nitrogen is available. The quantity of available nitrogen is reduced by losses in the form of ammonia. Conversely, N_2O emissions induced by ammonia (kg NH_3) are included.

Emissions of NOx to Air

During denitrification processes in soils, NO_x may also be produced (Harrison, 1999). These emissions were estimated, using the methodology outlined in (Nemecek & Kagi, 2007), from the emissions of N_20:

$NO_x = 0.21 * N_2O$

This is a parallel process, not one of conversion from N_2O to NO_x. Therefore no correction of the N_2O emissions is required. This equation includes the direct NO_x emissions from fertilisers and soils only. Other sources such as tractor exhausts are included in their respective inventories.

FARM MACHINERY

Weights and estimated lifetimes for different farm machinery were estimated from several sources. These included previous studies, agricultural data and information from farm machinery manufacturers (see Table E-2) (Nemecek & Erzinger, 2005; Nix, 2009).

Table E-2: Reference used for farm machinery data

Machinery	Reference
Tractor	http://www.deere.co.uk/
Broadcaster	http://www.spaldings.co.uk
Subsoiler	http://www.spaldings.co.uk
Plough	http://www.spaldings.co.uk
Disc harrow	http://www.spaldings.co.uk
Sprayer	http://www.spaldings.co.uk
Planter	http://www.standen.co.uk
Roller	http://www.spaldings.co.uk
Transplanter	http://www.standen.co.uk
Broadcaster	http://www.standen.co.uk
Self propelled forage harvester	http://www.claas.com/
Baler	http://www.masseyferguson.com/
Trailer	http://www.mas-trailers-group.co.uk/
Bale loader	http://www.masseyferguson.com/
Direct chip harvester	http://www.claas.com/

APPENDIX F. PERENNIAL ENERGY CROPS LCIA RESULTS AND SENSITIVITY ANALYSIS

Full results from the life cycle impact assessment (LCIA) of Miscanthus and SRC Willow from Chapter 6 are presented in this appendix. Further information and findings from the sensitivity analyses are also included for both crops.

MISCANTHUS

Full life cycle impact assessment (LCIA) results

Table F-1 displays the LCIA results for Miscanthus:

Table F-1: Life cycle impacts for the production of 1 kg of Miscanthus – LCIAM: ReCiPe

	Midpoint Results		Endpoint Results	
Impact category	**unit**	**Total**	**unit**	**Total**
Climate change Human Health	kg CO_2 eq	5.111E-02	DALY	7.155E-08
Climate change Ecosystems	-	N/A	species.yr	4.052E-10
Ozone depletion	kg CFC-11 eq	4.029E-09	DALY	1.058E-11
terrestrial acidification	kg SO_2 eq	2.761E-04	species.yr	1.602E-12
freshwater eutrophication	kg P eq	5.736E-05	species.yr	2.550E-12
marine eutrophication	kg N eq	4.191E-05	species.yr	0.000E+00
human toxicity	kg 1,4-DB eq	4.540E-03	DALY	3.178E-09
photochemical oxidant formation	kg NMVOC	3.752E-04	DALY	1.463E-11
particulate matter formation	kg PM10 eq	1.267E-04	DALY	3.294E-08
terrestrial ecotoxicity	kg 1,4-DB eq	4.210E-06	species.yr	5.353E-13
freshwater ecotoxicity	kg 1,4-DB eq	9.666E-05	species.yr	7.542E-14
marine ecotoxicity	kg 1,4-DB eq	1.240E-04	species.yr	1.042E-15
ionising radiation	kg U_{235} eq	5.132E-03	DALY	8.418E-11
agricultural land occupation	m^2a	3.587E-04	species.yr	4.091E-12
urban land occupation	m^2a	4.860E-04	species.yr	9.379E-12
natural land transformation	m^2	1.947E-05	species.yr	3.095E-11
water depletion	m^3	4.509E-04	$	0.000E+00
metal depletion	kg Fe eq	6.428E-03	$	4.595E-04
fossil depletion	kg oil eq	1.288E-02	$	2.070E-01

Sensitivity Analysis

Table F-2 shows the sensitivity cases assessed for Miscanthus. A summary of the effects on the main emissions and resource consumption relative to the base case for each sensitivity case is shown in Table F-3. The percentages shown represent the deviation from the base case values (see Table F-1), when comparing results on a per unit of biomass produced (i.e. 1kg) basis. The positive numbers indicate a percent increase in the impact category while the negative numbers signify a decrease.

Table F-2: Sensitivity analysis cases for the production of Miscanthus

Case letter	Sensitivity case	Base case	Sensitivity	Change from base case
A	Micro-propagation instead of rhizomes	Harvesting of rhizomes	Micro-propagation	different method
B	No lime is applied	3 tonnes of lime	0 tonnes	-3,000 kg
C	Specialist Miscanthus planter used	Potato planter	Miscanthus planter	different method
D	No herbicide applied	4 litres of herbicide	0 litres	-4 litres
E	High herbicide application	4 litres of herbicide	72 litres	+68 litres
F	No fertilisers applied	100 kg N 40 kg P 60 kg K	0 kg of NPK	-100 kg N -40 kg P -60 kg K
G	High nitrogen (N) applications	100 kg N	100 kg N (per year) 1,800 kg N (total)	+1,700 kg
H	High phosphate (P) applications	40 kg P	20 kg P (per year) 280 kg P (total)	+240 kg
I	High potassium (K) applications	60 kg K	100 kg K (per year) 1,800 kg K (total)	+1,700 kg
J	High NPK Fertiliser applications	100 kg N 40 kg P 60 kg K	1,800 kg N 280 kg P 1,800 kg K	+1,700 kg N +240 kg P +1,700 kg K
K	Organic fertiliser	Inorganic fertiliser	Organic fertiliser	different material
L	Alternative harvesting method	Self propelled forage harvester & baling	Self propelled forage harvester & chopping	different method
M	Different drying method 1	Natural drying	Drying in storage	different method
N	Different drying method 2	Natural drying	Drying in industrial applications	different method
O	Storage	Storage barn constructed	Use existing buildings	different method
P	Water use: Irrigation 1 (low)	Sufficient rain water	1,000 m^3 irrigation water per year	+1,000 m^3
Q	Water use: Irrigation 2 (medium)	Sufficient rain water	5,000 m^3 irrigation water per year	+5,000 m^3
R	Water use: Irrigation 3 (high)	Sufficient rain water	10,000 m^3 irrigation water per year	+10,000 m^3

Table F-3: Sensitivity analysis results for Miscanthus cases A-R (% change from the base case)

		Sensitivity Case Letter																	
Impact category	**Unit**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**	**R**
climate change	kg CO2 eq	-2.4	-7.5	-2.0	-0.8	29.7	-9.8	115.4	3.9	13.1	132.3	-9.5	7.7	1.2	21.4	-27.4	2.4	13.4	24.4
ozone depletion	kg CFC-11 eq	-2.2	-2.4	-3.3	-1.4	49.7	-7.7	77.6	6.0	21.2	104.8	-7.2	10.9	0.7	41.9	-12.5	2.7	14.8	26.9
terrestrial acidification	kg SO2 eq	-4.2	-2.4	-3.1	-0.8	31.0	-17.1	213.3	5.3	7.4	225.9	-6.0	10.4	0.7	3.1	-9.2	1.5	8.5	15.5
freshwater eutrophication	kg P eq	-8.9	-0.1	0.0	0.0	0.8	-87.6	1.2	525.2	0.6	527.0	-87.6	0.5	0.0	0.1	-0.5	0.2	1.1	2.0
marine eutrophication	kg N eq	-4.0	-2.2	-3.8	-0.5	17.9	-10.7	129.6	4.7	6.1	140.4	-5.2	12.4	0.3	1.8	-8.1	1.1	5.8	10.6
human toxicity	kg 1,4-DB eq	-2.9	-1.9	-0.4	-0.8	29.2	-6.5	61.2	7.3	15.4	83.8	-6.3	2.8	1.6	1.9	-49.4	3.8	21.0	38.1
photochemical oxidant formation	kg NMVOC	-3.6	-2.3	-3.9	-0.5	19.2	-5.4	58.9	4.5	6.6	70.1	-2.9	13.1	0.3	2.9	-8.3	1.4	7.5	13.7
particulate matter formation	kg PM10 eq	-3.8	-2.2	-3.4	-0.7	24.9	-8.8	100.2	6.0	8.0	114.1	-4.4	12.3	0.4	2.1	-9.0	1.8	9.7	17.7
terrestrial ecotoxicity	kg 1,4-DB eq	-3.2	-1.8	-2.3	-1.6	60.8	-9.5	84.5	16.2	11.3	112.1	-9.2	9.2	0.4	4.7	-18.6	4.0	21.7	39.5
freshwater ecotoxicity	kg 1,4-DB eq	-3.1	-1.5	-0.8	-0.5	17.4	-6.1	47.1	10.7	17.8	75.7	-5.9	10.5	0.8	1.7	-24.8	4.3	23.8	43.3
marine ecotoxicity	kg 1,4-DB eq	-3.5	-1.3	-0.9	-0.8	28.5	-6.9	67.5	6.1	18.7	92.3	-6.6	9.5	0.8	3.9	-22.4	4.3	23.7	43.1
ionising radiation	kg U235 eq	-2.1	-5.1	-0.6	-2.9	106.2	-4.8	37.2	8.1	16.1	61.3	-4.3	9.9	3.3	4.7	-33.8	57.9	318.3	578.8
agricultural land occupation	m2a	-3.5	-3.8	-0.4	-0.9	34.9	-15.6	151.9	7.8	65.3	225.0	-15.3	5.6	0.1	3.2	-33.5	48.8	268.4	487.9
urban land occupation	m2a	-1.5	-0.7	-0.4	-0.3	10.3	-5.8	32.5	6.9	50.3	89.7	-5.3	2.7	0.1	1.8	-70.5	14.5	79.6	144.7
natural land transformation	m2	-1.9	-1.9	-2.7	-0.9	31.3	-3.9	42.6	4.0	1.8	48.4	-3.5	8.9	0.6	12.6	-33.2	1.1	5.8	10.5
water depletion	m3	-1.4	-30.0	-0.4	-0.4	15.5	-2.8	23.0	3.0	13.4	39.4	-2.7	2.2	3.1	1.0	-42.8	1,125	6,188	11,251
metal depletion	kg Fe eq	-4.4	-0.4	-0.4	-0.3	10.1	-5.4	53.5	2.6	22.6	78.6	-5.3	12.4	0.0	2.3	-8.2	6.4	35.4	64.4
fossil depletion	kg oil eq	-2.7	-3.6	-2.9	-1.5	53.5	-7.2	72.7	5.4	19.8	97.9	-6.7	10.5	1.5	33.8	-12.2	3.8	20.9	38.0

SRC WILLOW

Full life cycle impact assessment (LCIA) results

Table F-4 displays the LCIA results for SRC Willow:

Table F-4: Life cycle impacts for the production of 1 kg of SRC Willow – LCIAM: ReCiPe

	Midpoint Results		Endpoint Results	
Impact category	**unit**	**Total**	**unit**	**Total**
Climate change Human Health	kg CO_2 eq	1.376E-01	DALY	1.927E-07
Climate change Ecosystems	-	N/A	species.yr	1.091E-09
Ozone depletion	kg CFC-11 eq	9.337E-09	DALY	2.462E-11
terrestrial acidification	kg SO_2 eq	1.050E-03	species.yr	6.090E-12
freshwater eutrophication	kg P eq	4.759E-04	species.yr	2.116E-11
marine eutrophication	kg N eq	1.064E-04	species.yr	0
human toxicity	kg 1,4-DB eq	9.692E-03	DALY	6.783E-09
photochemical oxidant formation	kg NMVOC	5.910E-04	DALY	2.305E-11
particulate matter formation	kg PM_{10} eq	2.802E-04	DALY	7.285E-08
terrestrial ecotoxicity	kg 1,4-DB eq	1.048E-05	species.yr	1.332E-12
freshwater ecotoxicity	kg 1,4-DB eq	1.661E-04	species.yr	1.296E-13
marine ecotoxicity	kg 1,4-DB eq	2.464E-04	species.yr	2.070E-15
ionising radiation	kg U_{235} eq	1.125E-02	DALY	1.845E-10
agricultural land occupation	m^2a	4.672E-03	species.yr	5.246E-11
urban land occupation	m^2a	1.212E-03	species.yr	2.340E-11
natural land transformation	m^2	2.987E-05	species.yr	5.822E-11
water depletion	m^3	7.263E-04	$	0
metal depletion	kg Fe eq	9.513E-03	$	6.799E-04
fossil depletion	kg oil eq	2.880E-02	$	4.633E-01

Sensitivity Analysis

Table F-5 shows the sensitivity cases assessed for SRC Willow. A summary of the effects on the main emissions and resource consumption relative to the base case for each sensitivity case is shown in Table F-6. The percentages shown represent the deviation from the base case values (see Table F-4), when comparing results on a per unit of biomass produced (i.e. 1kg) basis. The positive numbers indicate a percent increase in the impact category while the negative numbers signify a decrease.

Table F-5: Sensitivity analysis cases for the production of SRC Willow

Case letter	Sensitivity case	Base case	Sensitivity	Change from base case
A	Willow rods used instead of cuttings	Willow cuttings	Willow rods	different method
B	No lime is applied	3 tonnes of lime	0 tonnes	-3,000 kg
C	Modified cabbage planter used	Transplanter	Modified cabbage planter	different method
D	No herbicide applied	80 litres of herbicide	0 litres	-80 litres
E	High herbicide application	80 litres of herbicide	160 litres	+80 litres
F	No fertilisers applied	200 kg N 42 kg P 100 kg K	0 kg of NPK	-200 kg N -42 kg P -100 kg K
G	High nitrogen (N) application	200 kg N	300 kg N (per 3 yrs)	+100 kg
H	High phosphate (P) application	42 kg P	100 kg P (per 3 yrs)	+58 kg
I	High potassium (K) application	100 kg K	267 kg K (per 3 yrs)	+167 kg
J	High NPK Fertiliser application	200 kg N 42 kg P 100 kg K	300 kg N (per 3 yrs) 100 kg P (per 3 yrs) 267 kg K (per 3 yrs)	+100 kg N +58 kg P +167 kg K
K	Organic fertilisers	Inorganic fertilisers	Organic fertilisers	different material
L	Alternative harvesting method	Direct chip harvesting	Billet harvesting	different method
M	Different drying method 1	Natural drying	Drying in storage	different method
N	Different drying method 2	Natural drying	Drying in industrial applications	different method
O	Storage	Storage barn constructed	Use existing buildings	different method
P	Water use: Irrigation 1 (low)	Sufficient rain water	1,000 m^3 irrigation water per year	+1,000 m^3
Q	Water use: Irrigation 2 (medium)	Sufficient rain water	5,000 m^3 irrigation water per year	+5,000 m^3
R	Water use: Irrigation 3 (high)	Sufficient rain water	10,000 m^3 irrigation water per year	+10,000 m^3

Table F-6: Sensitivity analysis findings for SRC Willow cases A-R (% change from the base case)

		Sensitivity Case Letter																	
Impact category	**Unit**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**	**R**
climate change	kg CO2 eq	-8.1	-3.3	-0.2	-6.2	6.2	-62.0	26.4	2.3	4.3	24.4	-60.0	-1.0	0.6	6.6	-11.7	1.4	6.2	11.0
ozone depletion	kg CFC-11 eq	-6.8	-1.2	-0.4	-12.1	12.1	-58.2	20.5	4.2	8.2	16.4	-54.9	-1.8	0.7	14.7	-5.9	1.9	8.0	14.2
terrestrial acidification	kg SO2 eq	-10.0	-0.7	-0.2	-4.3	4.3	-73.7	34.6	2.2	1.5	35.2	-25.5	-1.1	0.4	0.9	-2.6	0.8	2.9	5.1
freshwater eutrophication	kg P eq	-12.5	0.0	0.0	-0.1	0.1	-87.3	0.1	130.5	0.1	130.6	-87.3	0.0	0.0	0.0	-0.1	0.0	0.2	0.3
marine eutrophication	kg N eq	-9.4	-1.0	-0.4	-2.9	2.9	-68.4	31.3	2.6	1.8	32.2	-33.1	-2.0	0.6	1.1	-3.3	1.0	3.2	5.5
human toxicity	kg 1,4-DB eq	-6.3	-1.0	-0.1	-8.3	8.3	-51.2	17.7	6.8	6.7	17.7	-50.3	-0.2	0.8	0.8	-27.2	2.3	11.7	21.2
photochemical oxidant formation	kg NMVOC	-7.2	-1.8	-0.6	-5.1	5.1	-54.9	22.7	3.9	3.1	23.6	-29.5	-3.2	1.0	2.3	-5.4	1.9	6.5	11.1
particulate matter formation	kg PM10 eq	-8.5	-1.2	-0.4	-5.5	5.5	-64.3	27.8	4.4	2.9	29.3	-31.9	-2.0	0.7	1.3	-4.3	1.5	5.7	10.0
terrestrial ecotoxicity	kg 1,4-DB eq	-6.4	-0.9	-0.3	-14.5	14.5	-57.3	20.8	12.7	4.0	29.5	-55.5	-1.2	0.4	1.8	-8.5	2.2	10.6	19.1
freshwater ecotoxicity	kg 1,4-DB eq	-7.6	-1.0	-0.2	-5.7	5.7	-58.2	16.8	12.3	9.6	19.6	-57.0	-0.6	0.5	1.0	-16.8	3.2	16.6	30.0
marine ecotoxicity	kg 1,4-DB eq	-7.6	-0.8	-0.2	-8.4	8.4	-60.5	20.9	5.8	8.7	18.0	-58.3	-0.6	0.5	1.7	-13.2	2.7	14.2	25.7
ionising radiation	kg U235 eq	-1.5	-2.8	-0.2	-30.2	30.2	-37.0	10.3	7.2	6.8	10.7	-33.4	-0.4	0.7	1.2	-18.6	30.5	170	309
agricultural land occupation	m2a	-3.1	-0.3	0.0	-1.6	1.6	-23.1	7.2	1.2	4.7	3.6	-22.6	0.0	0.0	0.2	-3.0	4.4	24.3	44.2
urban land occupation	m2a	-7.0	-0.3	-0.1	-2.4	2.4	-51.3	8.0	5.5	19.1	-5.6	-47.9	-0.2	0.1	0.6	-33.3	6.9	37.7	68.4
natural land transformation	m2	-4.1	-1.5	-0.5	-11.1	11.1	-38.3	16.8	4.0	0.5	20.3	-34.3	-2.3	0.9	7.1	-25.1	1.4	5.1	8.7
water depletion	m3	-4.0	-22.0	-0.1	-5.8	5.8	-33.0	8.8	3.6	7.8	4.6	-32.0	-0.3	1.8	0.8	-31.1	826	4,541	8,256
metal depletion	kg Fe eq	-9.6	-0.3	-0.2	-3.6	3.6	-70.3	22.2	3.1	14.2	11.0	-69.5	-0.4	0.0	1.2	-6.5	5.1	28.2	51.3
fossil depletion	kg oil eq	-6.3	-1.9	-0.3	-13.8	13.8	-56.4	19.9	3.9	8.0	15.8	-53.1	-1.7	1.0	12.4	-6.0	2.5	11.6	20.6

APPENDIX G. BIOMASS GASIFICATION SUPPORTING LIFE CYCLE INVENTORY DATA

PLANT CONSTRUCTION

Sustainable Energy Ltd (SE) supplied a schedule of the equipment, instruments and the electrical specifications and cabling contained within the plant. For equipment, the information provided included the name of the item, a description, and the manufacturer. Equipment items have been grouped together due to the high number of items (see Table G-1). Items of equipment inside the skid unit are numbered 1 to 38, and outside (O) the skid unit (O1 to O13), based on the SE schedule. Table G-1 summarises each group of items.

Table G-1: Main groups of items included in the plant construction inventory

Name	Description	Items	Item numbers
Outside enclosure	Steel and coating used around the outside of the buildings	Steel sheets and metal coating	n/a – calculated
Steel structure	Steel beams, stairs and flooring used for structure of skid unit.	See description	n/a – calculated
Biomass silo	Provides storage and supply of wood chips (sawdust), located outside the main skid unit	Biomass Silo, primary biomass feedscrew, rotary valve, rotary agitator	O1, O2, O3 & O4
Feed hopper	Where the wood chips first enter the main skid unit and feed into the gasifier	Feed hopper, spiral conveyor, feed agitator, inlet venturi	1, 2, 3 & 4
Valves	A series of valves used to control the flow of feedstock into the gasifier	Biomass slide valve, actuated valve, air inlet slide valve, char rotary valve	5, 6, 7 & 8
Pre-burner	Used to pre-heat the gasifier	MP10 burner fired on natural gas	9
Ash disposal	Lower part of the gasifier which collects the ash for disposal	Ash rotary valves, ash conveyor, ash char filter and ash disposal bin	10, 11, 12, 15 & O5
Gasifier	Main part of the gasifier where the gasification reactions occur	Gasifier, reactor vessel, cyclone section and feed-air preheater.	13 & 14
Scrubber	Producer gas is mixed with water to cool the gas down and clean the gas to remove potential contaminants from the gas.	Air inlet screen, air bypass valve, gas quench, venturi scrubber, impingement plate scrubber, scrubber sump & sight glass	16-21 & 35
Pump & blower	These provide the mechanical energy for the gas flow around the system.	Scrubber circulation pump & Roots blower	22-24
Aftercooler & demister	Used to cool the producer gas and remove condensate	Gas aftercooler, coolant pump, expansion vessel, vent, demister & pump	25 & 27-30
Solvent handling	Effluent which is removed from the gas in the scrubbing process is collected outside the skid unit.	Solvent pump, storage vessel, effluent filter, actuated valve and effluent collection tank	31, 33, O7, O8 & O10
Heat exchanger	Captures the useful heat energy from the system to use as CHP.	Circulating water cooler, dry air cooler, ventilation fan and control valve	O6, O9, 34 & 37
Outside the skid	Valves and piping which is housed outside the skid unit.	Pressure relief valve, temp control valve & gas drop valve	O11-O13
Gas engine 250 kW	Utilises the producer gas for electricity.	Internal combustion engine	n/a
Instruments	Various instruments used to control the operation of the plant	Switches, sensors, flow meters, temperature gauges, pressure gauges, transmitters, etc.	See instrument schedule
Electrical specification	Cabling used in the electrical control equipment	Cabling	

Stainless steel LCI data

Type 316 stainless steel (316 ss) is the most commonly used material in Biomass Gasification Plant (BGP) construction, but it is not included within the Ecoinvent database. Therefore, a new material was made within Simapro based on the composition of 316 ss. British Standard EN 10088-2 is the material standard for stainless steel (British Standards Institute, 2005), this composition was used to create a new material in Simapro.

Stainless steel, which contains iron, chromium, and often nickel, molybdenum, and other elements, is an alloy with a wide range of applications. Its anti-corrosion properties are among the key features of its use in industry. In the construction of the biomass gasification plant, stainless steel is easily the highest material consumed. As a starting point for creating a new material in SimaPro, the British Stainless Steel Association (BSSA) was contacted to establish the production methods of UK stainless steel. The International Stainless Steel Forum (ISSF) was also contacted and they provided LCI data for European stainless steel (Camilla Kaplin, ISSF, February 2010, personal communication).

The BSSA confirmed that all stainless steel produced in the UK and most of Europe uses an electric arc furnace (EAF) for melting. Temperatures in the EAF reach around 1,500°C, so are very energy intensive. According to a study made by the ISSF, the global average for recycled content in stainless steel is 60%. This figure was consistent with the BSSA, which stated that the recycled material used during manufacturing is 60-70% (Alan Harrision, BSSA, February 2010, personal communication). Therefore, it was assumed that 60% of the input to the process is from stainless steel scrap. The remaining 40% is obtained from virgin production, i.e. primary raw materials.

In undertaking this research, it was found that the data available for grade 304 ss could be improved and updated. The main reasoning for this is that in the existing data, the primary production assumes the use of a blast oxygen furnace and that the recycled content is zero. This is not consistent with the information obtained from the BSSA and the ISSF, so it was decided to improve the data. Having obtained similar data for type 316 ss, it was relatively simple to also create a new material for type 304 ss.

BS EN 10088-2 is the material standard for stainless steel (British Standards Institute, 2005), this gives the composition of both 304 ss and 316 ss, as shown in Table G-2 (N.B. figures shown are percentages, the remaining amount is Iron (Fe)):

Table G-2: Composition of stainless steel types 304 and 316 (BS EN 10088-2:2005)

Steel name	Steel number	C	Si	Mn	P	S	N	Cr	Mo	Ni
		Percentage (%)								
304	1.4301	0.07	1.00	2.00	0.045	0.015	0.11	17.5/19.5	-	8.0/10.5
316	1.4401	0.07	1.00	2.00	0.045	0.015	0.11	16.5/18.5	2.00/2.50	10.0/13.0

Key: Fe = Iron (Fe from Latin ferrum); C = Carbon; Cr = Chromium; Ni = Nickel; Mo = Molybdenum; Ti = Titanium; Mn = Manganese; Si = Silicon; S = Sulphur; N = Nitrogen.

Several sources were used to obtain data on the material and energy inputs into stainless steel production, and the associated emissions. The main sources were the BSSA, ISSF and Ecoinvent. A summary of the main inputs for the production of 1 kg of stainless steel (304 and 316) is provided in Table G-3.

Table G-3: Main inputs for the production of 1kg of stainless steel (types 304 & 316)

Input from Technosphere	304	316	Unit
Electric Arc Furnace (EAF)	4.0×10^{-11}	4.0×10^{-11}	P
Primary Energy	54.8	50.3	MJ
Crude oil	0.250	0.276	kg
Hard coal	0.820	0.600	kg
Lignite	0.083	0.067	kg
Natural gas	0.195	0.177	kg
UK electricity mix	0.424	0.424	kWh
Stainless steel scrap	0.6	0.6	kg
Iron ore	0.285	0.273	kg
Ferrochromium	0.07	0.066	kg
Ferronickel	0.032	0.04	kg
Molybdenum	0	0.008	kg

Emissions data for the relevant inputs was taken from Ecoinvent (Swiss Centre for Life Cycle Inventories, 2009).

Outside enclosure

In Chapter 7, Figures 7-1 and 7-2 show the main building used to house the gasification skid unit. The outside enclosure is made entirely from steel, and is coated with a grey metal coating. It consists of the walls, roof and doors, but does not include the flooring. REL Ltd manufactured the outside enclosure using grade 316 stainless steel plates. Dimensions of the steel plates are as follows:

- Front and rear walls = 10,000mm x 3,421mm = 34.21 m^2
- Side walls = 3,000mm x 3,421mm = 10.26 m^2
- Roof = 10,000mm x 3,000mm = 30 m^2

This gives a total area of 74.47 m^2. All plates are 6mm in thickness, and are hot rolled to fabricate the metal into sheets. British Standard EN 10025-3 states that the nominal mass is determined from the nominal dimensions using a volumetric mass of 7,850kg/m^3 (British Standards Institute, 2004). As the plates are 6mm thick, the mass per metre is: 47.1 kg/m^2, (i.e. 7,850kg *.006m). Therefore, the total mass of the outside enclosure is 3,508kg, (i.e. 47.1 kg/m^2 * 74.47 m^2). Materials used in the outside enclosure are summarised in Table G-4:

Table G-4: Materials used in outside enclosure

Item name	Materials Used	Company /Supplier	Data Collection Method
Outside Enclosure	3,508 kg Stainless steel (316)	REL Ltd	2
	75.47 m^2 Metal coating		2

In addition to materials, the stainless steel is processed using hot rolling, average metal working is assumed, and welding is also included in the inventory.

Steel structure

Figure G-1 shows the steel structure being manufactured at REL. The total amount of steel used in the structure was more complicated to calculate than the outside enclosure, due to the number and type of beams used. In addition to the steel beams, the flooring and steps are also included. SE supplied the engineering diagrams for the ground floor, first floor and side view. These contained the type of beam and size, but the length of each beam had to be measured by hand using the scale diagram.

Figure G-1: Steel structure being manufactured by REL Ltd

The steel structure consisted of the ground floor structure, flooring, support beams, uprights, diagonals, and the first floor. The following types of structural steelwork were used in the plant:

- Parallel Flange Channels (PFC)
- Rolled Steel Angles (RSA)
- Universal Beams (UB)
- Square Hollow Sections (SHS)
- Circular Hollow Sections (CHS)
- Floor plates
- Open mesh flooring
- Stairs

These were of various lengths, sizes, quantities, thicknesses, and mass. Due to the total number of calculations performed, the full calculations are not included here. Instead a worked example is given for one item of structural steelwork (see below) and a summary is presented in Table G-5. As the lengths vary considerably, each length was calculated individually. Therefore, only the quantity and the total weight for each type are included in the table.

Worked example:

- PFC, 150mm x 75mm (size), 18mm (thickness).
- The mass per metre for 18mm is 17.9 kg/m (British Standards Institute, 2004).
- Therefore for a length of 2.7m, the total mass is 48.33 kg (i.e. 17.9 * 2.7)

All items of the structural steelwork confirm to British Standard EN 10025-3, so the mass per metre is taken from this.

Table G-5: Types of structural steelwork, quantity and total weight

Type	Size(s)	Thickness (mm)	Mass per metre (kg/m)	Quantity*	Total Weight (kg)
PFC	150x75 260x90	18 35	17.9 34.8	44	2,677
RSA	100x65 75x50 100x100	7 6 8	8.77 5.65 12.2	44	435
UB	178x102	19	19	5	277
SHS	100x100 80x80	8 5	22.6 11.6	16	403
CHS	76.1x3.2	3.2	5.75	4	79
Floor Plates	300x300	10	28.3	272	1,238
Open mesh flooring	300x300	10	18	100	292
Stairs	600x190 600x600	10	18	11	27
TOTAL					**5,427 kg**

* There are several different lengths

By going through the engineering diagrams, quantifying the different types of structural steelwork and calculating the weights for each item, the total weight of stainless steel was calculated as 5,427 kg, as summarised in Table G-6:

Table G-6: Materials used in steel structure

Item name	Materials Used	Company /Supplier	Data Collection Method
Steel structure	5,427 kg Stainless steel (316)	REL Ltd	2

In addition to materials, the stainless steel is processed using hot rolling, average metal working is assumed, and welding is also included in the inventory.

Biomass silo

The biomass silo (O1) was manufactured by Wood Waste Control ltd (WWC). It was not possible to obtain the exact weights of all materials directly from WWC. However, they provided details of the after filter and feed system, which used 390 kg of galvanised steel (Mike Edwards, WWC, November 2008, personal communication,). WWC confirmed the materials used in the silo, and the weights were calculated based on the information obtained. The biomass silo is 8m high and 3m in diameter and uses a 3mm thick mild steel. The leg supports are 3m high, so the main silo is 5m plus the coned base. The total weight of the steel was calculated based on the surface area of the steel plates used (56.5m^2), using a mass per metre of 23.55 kg/m^2 (British Standards Institute, 2004). The leg supports weighed an additional 182kg. Metal coating is assumed to be applied at 1 kg per m^2.

Details of the materials used in the agitator, rotary valve and feedscrew (O2-O4) were provided directly by WWC Ltd. Standard metal working and machinery processes were assumed for all items in the biomass silo. Table G-7 summarises the inventory data for the group of items in the biomass silo.

Table G-7: Materials used in Biomass silo

Equipment Item	Material Used	Company /Supplier	Data Collection
Primary biomass silo (O1)	1,514kg Mild steel	WWC Ltd	2
after filter feed system	390kg Zinc alloyed steel		1
	56.5kg Metal coating		2
Biomass silo agitator (O2)	6kg Stainless steel (316)		1
	0.2kg Copper		1
Rotary Valve (O3)	9kg Stainless steel (316)		1
Primary biomass feed screw (O4)	133kg Mild steel		1
	6kg Mild steel		1
	0.2kg Copper		1
	3kg Metal coating		1

Feed hopper & valves

Spiroflow Ltd manufactured the feed hopper (1), screw feeder (2) and agitator (3). Contact was made with Spiroflow Ltd who supplied the dimensions and materials of the items, from which the weights were calculated. The feed hopper and screw feeder were manufactured from mild steel, whilst the agitator also contained a motor. REL Ltd manufactured the inlet venturi (4) from grade 316 stainless steel.

The rotary and motorised slide valves (5, 7 & 8) were manufactured by Rotolok Ltd, who provided full details of the type and weights of materials used (Richard Collier, Rotolok Ltd, October 2008, personal communication). These used a mild steel and general steel working to fabricate to the required design. RS manufactured the solenoid valve (6) using a variety of materials, as described in Table G-8 (Rolland Higgins, RS, October 2008, personal communication). Standard metal working and machinery processes were assumed for all items in the feed hopper and valves.

Table G-8: Materials used in feed hopper & valves

Equipment Item	Material Used	Company /Supplier	Data Collection
Feed hopper			
Biomass feed hopper (1)	117kg Stainless steel (316)	Spiroflow Ltd	2
			2
Biomass feed spiral conveyor (2)	8kg Mild steel		
Biomass feed agitator (3)	6kg Stainless steel (316)		2
	0.2kg Copper		2
Biomass inlet venturi (4)	8kg Stainless steel (316)	REL Ltd	2
Valves			
Biomass slide valve (5)	9kg mild steel	Rotolok Ltd	1
	0.1kg Copper		1
Actuated Valve (6)	761g Brass	RS Ltd	1
	65g Mild steel		1
	7.5 g rubber		1
	221g Iron		1
	74g Copper		1
	179g zinc coating		1
Air inlet slide valve (7)	9kg mild steel	Rotolok Ltd	1
	0.1kg Copper		1
Char rotary valve (8)	27kg Mild Steel		1

Pre-burner

Nuway manufactured the MP10 pre-burner (9), see Table G-9. Data was obtained directly from the company who provided details of the type and weights of materials used (John Penrice, Nuway, October 2010, personal communication). It was not possible to obtain data on the production method, so a general manufacturing process was used from Ecoinvent.

Table G-9: Materials used in MP10 Pre-burner

Equipment Item	Material Used	Company /Supplier	Data Collection
Pre-heat burner (9)	2.1kg Stainless steel (304)	Nuway Ltd	1
	0.8kg Silicon carbide		1
	1.2kg Stainless steel (316)		1
	0.5kg Copper		1
	0.4kg Ceramic		1
	0.2kg Rubber		1

Gasifier (including ash disposal)

REL Ltd manufactured the feed air pre-heater (13); the gasifier (14) and the ash char filter (15). SE provided engineering diagrams for these items, from which the total mass of steel used was calculated. REL Ltd provided data on the grade 316 stainless steel and how it was manufactured.

Rotolok Ltd provided data on the two ash rotary valves used (10 & 11). Binder Ltd manufactured the screw feeder (12), which discharges ash from the bottom of the gasifier. It was not possible to make contact with Binder but SE provided the dimensions of the ash conveyor. Mild steel was used for the main part of the screw, with a motor and gear box to control the discharge.

An ash disposal bin (O5) is used to collect ash from the ash conveyor. Ridgeway manufactured the bin using mild steel sheets, fabricated using hot rolling and then welded together. The ‘1.0YD plus 300mm height increase’ tipping bin uses approximately 250kg of mild steel (Ian Detheridge, Ridgeway, October 2008, personal communication). Table G-10 summarises the materials used in producing the gasifier and ash disposal equipment. Where data on machinery use was not obtained from the company, average metal working and hot rolling of steel has been assumed.

Table G-10: Materials used in Gasifier and ash disposal

Equipment Item	Material Used	Company /Supplier	Data Collection
Gasifier			
Feed air pre-heater (13)	95kg Stainless steel (316)	REL Ltd	2
Gasifier (14)	740kg Stainless steel (316)		2
	20kg Rock wool		2
Ash disposal			
Ash rotary valve (10)	27kg Mild Steel	Rotolok Ltd	1
Ash rotary valve (11)	27kg Mild Steel		1
Ash conveyor (12)	145kg Mild steel	Binder Ltd	2
	0.2 kg Copper		2
Ash char filter (15)	8kg Stainless steel (316)	REL Ltd	2
Ash disposal bin (O5)	250kg Mild steel		1

Scrubber

The main parts of the scrubber were manufactured by Manrochem Ltd using grade 316 stainless steel. Manrochem replied but were unable to help with the request for data. Instead SE provided the engineering diagrams of the gas quench, venturi scrubber, impingement plate scrubber, and scrubber sump (18-21). From these the amount of steel used was calculated based on the dimensions and density of steel used.

MWA Ltd and Valves Online Ltd provided data on the materials used in the air filter (16) and air bypass valve (17). No data could be provided on the scrubber outlet sight glass (35). From inspection the sight glass is made from stainless steel and reinforced glass. Table G-11 summarises the materials used in the gas scrubber, average machinery working and hot rolling of steel has been assumed.

Table G-11: Materials used in the gas scrubber

Equipment Item	Material Used	Company /Supplier	Data Collection
Air inlet screen (16)	3.7kg Aluminium	MWA Ltd	1
	0.8kg Magnetite		1
	0.2kg Copper		1
Air bypass valve (17)	2.5kg Stainless steel (316)	Valves Online Ltd	1
	0.2kg PTFE		1
	1.5kg Aluminium alloy		1
	0.3kg Stainless steel (304)		1
Gas quench (18)	106kg Stainless steel (316)	Manrochem Ltd	2
Venturi scrubber (19)	130kg Stainless steel (316)		2
Impingement plate scrubber (20)	92kg Stainless steel (316)		2
Scrubber sump (21)	174kg Stainless steel (316)		2
Scrubber outlet sight glass (35)	4kg Stainless steel (304)		3
	0.8kg Reinforced glass		3

Pumps & blower

Mono Pumps Ltd manufactured the scrubber circulation pump (22), and Dresser Roots Ltd manufactured the roots blower (23). Both companies were able to provide a breakdown of the materials and weights used in the items (Ian Cambell, Mono Pumps, January 2009, personal communication; Matthew Fitzpatrick, Dresser Roots, October 2008, personal communication). Zook Ltd produced the bursting disk (24) entirely from stainless steel (James Harmisson, Zook Ltd, November 2008, personal communication). Table G-12 summarises the materials used in the pumps & blower, average machinery working and hot rolling of steel has been assumed.

Table G-12: Materials used in the pumps & blower

Equipment Item	Material Used	Company /Supplier	Data Collection
Scrubber circulation pump (22)	6kg Flouroelastomer	Mono Pumps Ltd	1
	42kg Cast Iron		1
	28kg Stainless steel (304)		1
Roots blower (23)	69kg Cast Iron	Dresser Roots Ltd	1
	16kg Mild steel		1
	1kg Aluminium		1
	5kg Stainless steel (304)		1
	1.5kg Lubricating oil		1
	0.5kg Polyurethane		1
Bursting disk (24)	3.9kg Stainless steel (316)	Zook Ltd	1

Aftercooler & demister

REL Ltd manufactured the gas aftercooler (25) and demister (29) using grade 316 stainless steel. The amount of steel used was calculated, in the same way as the gasifier and scrubber, using engineering diagrams provided by SE. Iowara Ltd produced the coolant pump (27), but did not provide data on the materials used. These were obtained from a company manual which provided dimensions of the pump, from which the amounts of materials were calculated. The expansion vessel (28), produced by BSS Ltd, was made from mild steel and a powder coating. This data was obtained from the company website and through an estimate of weight based on size and density. Albany pumps manufactured the condensate pump (30), and were able to provide data on the weights and materials used. Table G-13 summarises the materials used in the aftercooler & demister. Standard metal working and machinery processes were assumed for all items.

Table G-13: Materials used in aftercooler & demister

Equipment Item	Material Used	Company /Supplier	Data Collection
Gas aftercooler (25)	102kg Stainless steel (316)	REL Ltd	2
Coolant pump (27)	18kg Cast Iron	Iowara Ltd	2
	7kg Stainless steel (316)		2
	2.5kg Mild steel		2
	0.3kg Nickel-plated brass		2
	1.3kg Aluminium		2
	0.5kg Ceramic		2
	0.2kg Zinc alloyed steel		2
Expansion vessel and vent (28)	5kg Mild steel	BSS Ltd	2
	0.6kg Metal coating		2
Demister and drop-out vessel (29)	120kg Stainless steel (316)	REL Ltd	2
Condensate pump (30)	26kg Cast iron		2
	10.3kg Stainless steel (316)		2
	3kg Mild steel		2
	0.3kg Nickel-plated brass		2
	1.7kg Aluminium		2
	0.5kg Ceramic		2
	0.2kg Metal coating		2

Solvent handling

Michael Engineers manufactured the micro gear pump (31). A company manual was obtained which gave the total weight of the pump and the materials used. However, the individual weights of material had to be estimated based on the dimensions provided in the manual. The solvent storage vessel (33) was made from entirely from mild steel by REL. The weight was calculated based on the engineering diagram provided by SE.

HECO produced the self cleaning effluent filter (O7). The company provided a breakdown of the materials used to produce the filter. Valves online produced the actuated valve (O8), details of its materials were obtained from the company website. The effluent collection tank (O10) is made from polyethylene and steel. No manufacturer details were provided, so the weights of materials were estimated from measuring the tanks' dimensions.

Table G-14: Materials used in solvent handling

Equipment Item	Material Used	Company /Supplier	Data Collection
Solvent pump (31)	18.4kg Stainless steel (316)	Michael Engineers Ltd	2
	3.4kg Carbon graphite		2
	0.4kg PEEK		2
	0.3kg Polypropylene		2
	0.15kg Viton		2
	0.35kg PTFE		2
Solvent storage vessel (33)	46kg Mild steel	REL Ltd	2
Self cleaning effluent filter (O7)	18.2kg Stainless steel (316)	HECO Ltd	1
	0.2kg PEEK		1
	0.1kg PTFE		1
	2.7kg Mild steel		1
	0.15kg Rubber		1
Effluent Discharge valve (O8)	2.5kg Mild steel	Valves Online	1
	0.8kg Stainless steel (316)		1
	0.2kg Metal coating		1
	0.1kg Polyester		1
	0.1kg Copper		1
Effluent collection tank (O10)	4kg Mild steel	Unknown	2
	6kg Polyethylene		2

Heat exchanger (including pipes)

TCI manufactured both the circulating water cooler (O6) and the dry air cooler (O9). Details of the materials used were obtained from the company website. However, it was not possible to obtain exact breakdowns of weight for each type of material. Therefore the weight of each material was estimated based on the total weight of 60kg and a physical inspection of the coolers.

Power Plus Engineering manufactured the ventilation fan (34). They were able to supply the weight and type of materials used, and the manufacturing processes. Valves Online produced the heat transfer liquid control valve (37); details of its materials were obtained from the company website.

Pipes around the plant were physically measured to obtain the length of piping. The thickness of the pipes varied, depending on the function and position of the pipe.

Table G-15: Materials used in heat exchanger

Equipment Item	Material Used	Company /Supplier	Data Collection
Heat transfer liquid control valve (37)	0.5kg Metal coating	Valves Online Ltd	1
	0.7kg Polyester		1
	9.3kg Stainless steel (304)		1
	0.3kg PTFE		1
	0.2kg Viton		1
Ventilation fan (34)	10.8kg Polyethylene	Power Plus Engineering Ltd	1
	2.4kg Brass		1
	2.1kg Printed wiring board		1
Circulating water cooler (O6)	9.2kg Aluminium	TCI Ltd	2
	4.2kg Copper		2
	2.5kg Copper piping		2
	44kg Zinc alloyed steel		2
Dry air cooler (O9)	9.2kg Aluminium	TCI Ltd	2
	4.2kg Copper		2
	2.5kg Copper piping		2
	44kg Zinc alloyed steel		2
Pipes	450kg Mild steel		2

Outside the skid

Flexachem produced the pressure relief valve (O11) and provided data on its construction. Valves Online produced the temperature control valve (O12); details of its materials were obtained from the company website. The gas drop valve (O13) was manufactured by Cogenco.

Table G-16: Materials used outside the skid unit

Equipment Item	Material Used	Company /Supplier	Data Collection
Pressure relief valve (O11)	16kg Cast iron	Flexachem Ltd	1
	2.4kg Stainless steel (316)		1
	3.6kg Aluminium		1
	1.3kg Hastelloy		1
Temp control valve for scrubber water (O12)	4.2kg Stainless steel (304)	Valves Online Ltd	1
	0.3kg Polyamide		1
	0.25kg PTFE		1
	0.8kg Mild steel		1
	0.1kg Silicon		1
Gas drop valve (O13)	26.6kg Cast iron	Cogenco Ltd	1
	3.3kg Mild steel		1
	1.2kg Stainless steel (304)		1
	0.7kg Graphite		1
	0.4kg Stainless steel (316)		1
	0.25kg Rubber		1
	0.18kg Zinc alloyed steel		1

Gas engine

Cogenco supplied the data for the material used in the gas engine (see **Error! Reference source not found.**)

Table G-17: Materials used in gas engine (source: Cogenco Ltd)

Gas engine	3,090kg Reinforcing steel
	5,090kg Low alloyed steel
	1,110kg Stainless steel (304)
	300kg Copper
	170kg Aluminium
	90kg Iron-nickel-chromium alloy
	75kg Polyethylene, HDPE
	75kg Polyvinylchloride

PLANT OPERATION

Natural gas burned in an industrial burner

Table G-18 shows the emissions to air from burning natural gas in an industrial burner. The data are taken from Ecoinvent and are based on the average composition of natural gas in the UK.

Table G-18: Emissions to air from burning natural gas in an industrial burner

Inputs from technosphere	
Natural gas, at consumer, Great Britain	1 MJ
Emissions to air	
Acetaldehyde	1.0×10^{-9} kg
Benzo(a)pyrene	1.0×10^{-11} kg
Benzene	4.0×10^{-7} kg
Butane	7.0×10^{-7} kg
Methane, fossil	2.0×10^{-6} kg
Carbon monoxide, fossil	2.0×10^{-6} kg
Carbon dioxide, fossil	0.056 kg
Acetic acid	1.5×10^{-7} kg
Formaldehyde	1.0×10^{-6} kg
Mercury	3.0×10^{-11} kg
Dinitrogen monoxide	5.0×10^{-7} kg
Nitrogen oxides	1.48×10^{-5} kg
PAH, polycyclic aromatic hydrocarbons	1.0×10^{-8} kg
Particulates, < 2.5 um	1.0×10^{-7} kg
Pentane	1.2×10^{-6} kg
Propane	2.0×10^{-7} kg
Propionic acid	2.0×10^{-8} kg
Sulfur dioxide	5.5×10^{-7} kg
Dioxins measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	3.0×10^{-17} kg
Toluene	2.0×10^{-7} kg

Electricity emissions

Table G-19 displays the emissions calculated for 1MJ of electricity produced from the UK Grid.

Table G-19: Calculated emissions from 1MJ of electricity from the UK grid– LCIAM: ReCiPe (midpoint)

Impact category	Unit	Total	Nuclear	Coal	Hydropower	Hydropower (pumped)	Wind	Oil	Natural gas	Coke oven gas
climate change	kg CO2 eq	1.69E-01	2.86E-04	9.75E-02	1.29E-05	2.64E-03	6.30E-05	4.60E-03	6.34E-02	4.47E-04
ozone depletion	kg CFC-11 eq	7.97E-09	6.83E-10	4.25E-09	8.69E-13	6.63E-11	4.01E-12	5.56E-10	2.37E-09	3.68E-11
terrestrial acidification	kg SO2 eq	5.31E-04	1.86E-06	4.26E-04	4.68E-08	8.16E-06	2.69E-07	5.57E-05	3.70E-05	1.81E-06
freshwater eutrophication	kg P eq	5.84E-06	1.57E-08	5.71E-06	9.41E-10	1.37E-08	8.70E-09	1.68E-08	7.23E-08	1.59E-09
marine eutrophication	kg N eq	3.22E-05	4.57E-07	2.05E-05	6.72E-09	6.33E-07	6.29E-08	2.49E-06	7.89E-06	1.51E-07
human toxicity	kg 1,4-DB eq	2.10E-02	1.06E-04	2.04E-02	1.36E-06	4.80E-05	2.08E-05	3.19E-04	1.21E-04	4.03E-06
photochemical oxidant formation	kg NMVOC	2.83E-04	1.48E-06	1.83E-04	6.32E-08	5.30E-06	2.04E-07	2.16E-05	6.70E-05	3.73E-06
particulate matter formation	kg PM10 eq	1.63E-04	7.39E-07	1.29E-04	7.55E-08	2.64E-06	1.83E-07	1.37E-05	1.54E-05	1.26E-06
terrestrial ecotoxicity	kg 1,4-DB eq	4.50E-06	3.39E-08	3.38E-06	8.48E-10	1.77E-07	7.65E-09	7.70E-07	1.17E-07	4.12E-09
freshwater ecotoxicity	kg 1,4-DB eq	2.09E-04	3.10E-06	1.96E-04	5.84E-08	8.07E-07	1.32E-06	5.19E-06	3.04E-06	5.94E-08
marine ecotoxicity	kg 1,4-DB eq	2.80E-04	3.27E-06	2.02E-04	6.28E-08	1.92E-06	1.46E-06	1.01E-05	6.09E-05	1.11E-07
ionising radiation	kg U235 eq	4.81E-02	4.35E-02	3.21E-03	2.09E-06	1.19E-03	1.28E-05	8.85E-05	8.23E-05	1.61E-05
agricultural land occupation	m2a	9.21E-05	1.37E-05	0.00E+00	1.37E-07	4.80E-05	1.26E-06	2.50E-06	8.43E-06	1.81E-05
urban land occupation	m2a	7.90E-05	8.03E-06	0.00E+00	3.76E-07	1.19E-05	5.24E-06	7.22E-06	4.19E-05	4.34E-06
natural land transformation	m2	3.27E-05	7.59E-08	0.00E+00	2.74E-09	8.05E-07	9.84E-09	2.22E-06	2.96E-05	3.29E-08
water depletion	m3	4.00E-03	2.70E-04	3.46E-03	1.67E-07	1.47E-05	6.41E-07	1.19E-05	2.39E-04	1.11E-06
metal depletion	kg Fe eq	8.49E-04	2.03E-04	3.68E-04	5.83E-06	2.02E-05	9.27E-05	2.33E-05	1.33E-04	2.78E-06
fossil depletion	kg oil eq	5.56E-02	8.73E-05	2.70E-02	3.00E-06	8.12E-04	1.95E-05	1.54E-03	2.59E-02	1.94E-04

APPENDIX H. BIOMASS GASIFICATION LCIA RESULTS AND SENSITIVITY ANALYSIS

Full results from the life cycle impact assessment (LCIA) of the biomass gasification CHP plant from Chapter 8 are presented in Table H-1. Further information and findings from the sensitivity analysis is found in Table H-2.

Table H-1: Life cycle impacts for the production of 1MJ of electricity from biomass gasification – LCIAM: ReCiPe

	Midpoint Results		Endpoint Results	
Impact category	**unit**	**Total**	**unit**	**Total**
Climate change Human Health	kg CO_2 eq	5.99E-03	DALY	8.39E-09
Climate change Ecosystems	-		species.yr	4.75E-11
Ozone depletion	kg CFC-11 eq	3.34E-10	DALY	8.45E-13
terrestrial acidification	kg SO_2 eq	2.37E-05	species.yr	1.37E-13
freshwater eutrophication	kg P eq	2.00E-05	species.yr	8.90E-13
marine eutrophication	kg N eq	6.21E-06	species.yr	0.00E+00
human toxicity	kg 1,4-DB eq	1.33E-03	DALY	9.32E-10
photochemical oxidant formation	kg NMVOC	1.60E-05	DALY	6.22E-13
particulate matter formation	kg PM10 eq	8.90E-06	DALY	2.31E-09
terrestrial ecotoxicity	kg 1,4-DB eq	2.66E-03	species.yr	3.38E-10
freshwater ecotoxicity	kg 1,4-DB eq	2.21E-03	species.yr	1.72E-12
marine ecotoxicity	kg 1,4-DB eq	2.90E-04	species.yr	2.44E-15
ionising radiation	kg U_{235} eq	3.06E-03	DALY	5.03E-11
agricultural land occupation	m^2a	6.57E-05	species.yr	7.38E-13
urban land occupation	m^2a	7.38E-05	species.yr	1.42E-12
natural land transformation	m^2	1.56E-06	species.yr	1.47E-12
water depletion	m^3	1.60E-04	$	0
metal depletion	kg Fe eq	0.001647	$	0.000118
fossil depletion	kg oil eq	0.002025	$	0.032564

A summary of the effects on the main emissions and resource consumption relative to the base case for each sensitivity case is shown in Table H-2. The percentages shown represent the deviation from the midpoint base case values (see Table H-1). The positive numbers indicate a percent increase in the impact category while the negative numbers signify a decrease.

Further details of the sensitivity analysis on the life cycle impact assessment (LCIA) results from the biomass gasification plant (BGP) are provided below. The information presented includes the complete LCIA results for each sensitivity case; why each case was chosen; the data used; and a description of the main findings.

Table H-2: Sensitivity analysis findings for biomass gasification plant operation

Sensitivity Case	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
	90% recycled steel	0% recycled steel	30 years	10 years	1000 hours	7000 hours	Feedstock composition	Diesel	Transporta tion	50 start-ups	300 start-ups	Low Ash	High Ash	Ash composition	Inert ash	Water energy	Water treatment	Waste water composition	Scrubbing fluids	Syngas emissions
Impact category																				
climate change	-2%	4%	-3%	10%	15%	-6%	n/a	-14%	22%	-6%	25%	0%	0%	n/a	0%	0%	0%	n/a	0%	0%
ozone depletion	-2%	3%	-6%	17%	25%	-11%	n/a	29%	61%	-4%	17%	0%	1%	n/a	-1%	0%	-1%	n/a	0%	0%
terrestrial acidification	-3%	5%	-5%	15%	22%	-9%	n/a	12%	16%	0%	2%	0%	0%	n/a	0%	0%	-1%	n/a	0%	668%
freshwater eutrophication	0%	0%	0%	0%	1%	0%	n/a	0%	0%	0%	0%	-49%	98%	n/a	-98%	0%	-1%	n/a	0%	0%
marine eutrophication	-1%	2%	-1%	4%	6%	-2%	n/a	30%	9%	0%	1%	0%	0%	n/a	0%	0%	-72%	n/a	0%	582%
human toxicity	-2%	5%	-9%	26%	39%	-17%	n/a	-6%	3%	0%	0%	-19%	38%	n/a	-38%	0%	-1%	n/a	0%	1200%
photochemical oxidant formation	-3%	5%	-5%	14%	21%	-9%	n/a	108%	36%	-1%	4%	0%	1%	n/a	-1%	0%	-1%	n/a	0%	2214%
particulate matter formation	-7%	13%	-8%	24%	36%	-16%	n/a	40%	19%	0%	2%	0%	0%	n/a	0%	0%	-1%	n/a	0%	698%
terrestrial ecotoxicity	0%	0%	0%	0%	0%	0%	n/a	0%	0%	0%	0%	-50%	100%	n/a	-100%	0%	0%	n/a	0%	3%
freshwater ecotoxicity	0%	1%	0%	1%	1%	-1%	n/a	0%	0%	0%	0%	-49%	99%	n/a	-99%	0%	0%	n/a	0%	1%
marine ecotoxicity	-3%	6%	-3%	8%	12%	-5%	n/a	0%	1%	0%	0%	-44%	89%	n/a	-89%	0%	0%	n/a	0%	3%
ionising radiation	-1%	2%	-2%	5%	8%	-3%	n/a	-63%	4%	0%	0%	0%	0%	n/a	0%	0%	0%	n/a	0%	0%
agricultural land occupation	-9%	5%	-7%	22%	33%	-14%	n/a	-41%	6%	0%	0%	0%	0%	n/a	0%	0%	0%	n/a	0%	0%
urban land occupation	-8%	14%	-7%	22%	33%	-14%	n/a	-1%	23%	0%	1%	0%	0%	n/a	0%	0%	-1%	n/a	0%	0%
natural land transformation	-5%	0%	-4%	11%	16%	-7%	n/a	37%	37%	-11%	45%	0%	0%	n/a	0%	0%	0%	n/a	0%	0%
water depletion	-1%	1%	-1%	4%	6%	-2%	n/a	-11%	3%	0%	0%	0%	0%	n/a	0%	0%	0%	n/a	0%	0%
metal depletion	-35%	71%	-29%	86%	129%	-55%	n/a	27%	3%	0%	0%	0%	0%	n/a	0%	0%	0%	n/a	0%	0%
fossil depletion	-5%	0%	-5%	14%	20%	-9%	n/a	-5%	23%	-8%	31%	0%	0%	n/a	0%	0%	0%	n/a	0%	0%

Plant Construction (sensitivity cases A & B)

Several sensitivities were considered to assess the plant construction results. Since the LCI data was reasonably comprehensive it was not considered necessary to assess every aspect of the plant construction. Similarly, as the predominant materials were all metals, the most useful and relevant sensitivity is the quantity of recycled metals used in the plant. Various sensitivity results were generated using different quantities and types of metals. The two main results are presented here to give an indication of the effect using a higher (or lower) recycled content has on the LCIA results.

The main type of metal consumed in the plant is stainless steel (grade 316), which is necessary due to its outstanding welding characteristics and corrosion resistance. It could not be substituted for another grade of steel; however a higher percentage of recycled materials could be used as an input. The assumption in the main study is that 60% of the elements used in stainless steel are derived from recycled sources. This is the average recycled content for UK stainless steel manufacturing; according to the BSSA this percentage could be increased to around 90% (Alan Harrision, BSSA, February 2010, personal communication). At the other extreme, all of the elements used in stainless steel could come from virgin sources (0% recycled content). These percentages were applied to all metals in the plant which was considered reasonable given the high amount of stainless steel consumed overall.

Findings from sensitivity case A showed that all impact categories were reduced, whilst in case B they all increased. The main effect of these two scenarios was on metal depletion. When 90% recycled metals were used (case A), each impact category was reduced, with mineral resource depletion reducing by 35% to 1.08kg Fe eq. per GJ of electricity produced. In contrast when virgin metals (0% recycled content) were used (case B), each impact category was increased and mineral resource depletion was found to increase by 71% to 2.81kg Fe eq. Therefore, the benefits of using recycled metals where possible are clear.

Plant lifetime and operating hours (cases C to F)

It is assumed that the BGP will remain operational for 20 years. This lifetime was selected based on the business model used for the plant, also in the UK feed-in tariffs are payable for 20 years on bioenergy systems (DECC, 2010a). As this is a new technology it is difficult to say exactly how long the plant may remain operational for. A number of previous studies were reviewed to assess possible alternative lifetimes for the plant. For example, 15 years (Carpentieri *et al*., 2005); 20 years or more (Andersons, 2010); 25 years (Elsayed *et al*., 2003); 30 years (Mann & Spath, 1997).

Given the capital investment in the plant and economic payback, a minimum plant lifetime of 10 years is expected. Once built, fossil-fuelled thermal power plant can last up to 40 years or more (Oliver, 2008). As a thermal generation plant, biomass gasification may also be expected to operate for up to 40 years, although the longer time scale is generally for larger scale power only plants. Since this plant is on a smaller scale and incorporates CHP it is more vulnerable to operating difficulties. Therefore the two sensitivities assessed for the plant lifetime were 30 years and 10 years (cases C & D).

Another assumption assessed is the number of operating hours the plant does each year. To remain economical, the plant must do a minimum of 1,000 operating hours per year. This was considered as the low case E, giving an operating capacity factor of 11%. At the other extreme, 7,000 operating hours (case F) is considered to be maximum number possible in one year, which gives a capacity factor of 80%.

Plant lifetime and operating hours both have a similar effect on the impact of the BGP. A longer lifetime of 30 years (or increased operating hours) will reduce the relative impact of plant construction and therefore reduce the impact of plant operation on a 'per MJ of energy produced' basis. However the overall impact of plant operation will increase with longer lifetime or more hours, as more energy will be produced. In contrast, a lifetime of 10 years (or decreased operating hours) will reduce the overall impact of plant operation, but will increase the relative impact on a 'per MJ of energy produced' basis.

To illustrate this more clearly an example is taken from the sensitivity analysis results for fossil fuel depletion. Table H-3 shows the effect of different plant lifetime on 'kg oil eq. per GJ of electricity' and the 'total kg of oil eq. consumed' assuming 2,500 hours; Table H-4 shows the effect of different operating hours assuming a 20 year lifetime.

Table H-3: Fossil fuel depletion for different plant lifetimes

Lifetime (Years)	kg oil eq. per GJ	Total kg oil eq.
10	2.30	47,620
20	2.02	83,816
30	1.93	120,013

Table H-4: Fossil fuel depletion for different annual operating hours

Operating hours (per annum)	kg oil eq. per GJ	Total kg oil eq.
1,000	2.44	40,381
2,500	2.02	83,816
7,000	1.85	214,123

Findings from the sensitivity analysis show that the length of time the plant is operational for has a direct affect on all impact categories. The examples presented demonstrate that each impact category will change in proportion to the time the plant operates for.

Feedstock composition (case G)

Feedstock composition (case G) is a complicated parameter to model quantitatively in the sensitivity analysis due to a lack of relevant data available. Essentially the composition of the feedstock will effect the composition of the ash, scrub water effluent, producer gas and subsequent emissions from combustion. Each of these parameters is assessed separately in the sensitivity analysis (see cases N, R and T respectively). Additionally, the feedstock composition will have an impact on the gasification conversion efficiency. Consequently the feedstock composition is assessed qualitatively here.

Appendix B shows the proximate and ultimate analyses for a range of biomass feedstocks. The data presented show that the composition of biomass feedstocks have considerable variability. It is beyond the scope of this thesis to assess the various permutations possible due to different feedstock compositions. Instead a brief description of the main likely effects on the LCIA results is assessed. Feedstocks which have a higher ash or moisture content will have lower gasification conversion efficiency. This will produce lower amounts of producer gas and higher amounts of ash, thus potentially lowering particulate matter formation and climate change, but increasing toxicity.

Feedstock pre-processing (case H)

Pre-processing the feedstock ready for gasification was assessed in the sensitivity analysis by assuming the use of a diesel powered wood-chipper (case H). The main effects of the diesel powered chipper in comparison to UK grid electricity were a small decrease in climate change (-14%) and fossil fuel depletion (-5%), but an increase in particulate matter formation (+40%) and metal depletion (+27%).

Feedstock transportation (case I)

In the case study wood waste is provided on site by a furniture factory, therefore no transportation is required. However, it is more common for bioenergy systems to require some feedstock transportation. Sensitivity case I assumes a transportation distance of 10km (20km round-trip) for the 500 tonnes of wood waste required per annum. The use of a 12t lorry has been assumed, which includes the allocated inventory for the operation, construction and maintenance of the lorry. The primary item included for operating the lorry is diesel consumption and the related emissions. Ecoinvent data was used which require the number of tonne-kilometres (tkm) to be used. In this case 10,000tkm are needed each year to deliver the feedstock to the plant, i.e. 500t @ 20km. This takes into account the return journey has an empty load by taking an average of the full and empty payload.

Sensitivity results for using transportation (case I) show increases to all impact categories. Most notable are the increases (on a per GJ of electricity basis) in fossil fuel depletion by 23% to 2.49 kg oil eq.; climate change by 22% to 7.23 kg CO_2 eq.; and particulate matter formation by 19% to 10.6g of PM10 eq. Metal depletion also increases, but only by 3% to 1.7kg Fe eq. The impact of transporting biomass feedstock in bioenergy systems is assessed in more detail in Chapter 10.

Number of start-ups – natural gas consumption (cases J & K)

Starting up and shutting down the plant primarily affects the amount of natural gas burned. A base case of 100 start-ups per year was assumed, although this may vary depending on the availability of feedstock, demand for energy and any possible maintenance requirements. The minimum number (low case J) considered in the sensitivity was 50 start-ups, as some maintenance is required on a weekly basis. At the other extreme, it is possible that the plant is started up on a daily basis for six days a week. Therefore a maximum number (high case K) of start-ups is 300.

Results of the sensitivity analysis show that the overall impact over the plant is not very sensitive to the number of start-ups. The exception to this is fossil fuel depletion and climate change, which both increase directly with more start-ups. When only 50 start-ups are assumed fossil fuel depletion decreases by 7.7% to 1.87 kg oil eq. and climate change decreases by 6.3% to 5.61 kg CO_2 eq. (on a per GJ of electricity basis). Conversely when 300 start-ups are assumed fossil fuel depletion increases by 30.8% to 2.65 kg oil eq. and climate change increases by 25.3% to 7.51 kg CO_2 eq. (on a per GJ of electricity basis). Therefore, to reduce the impact on energy use and climate change, the number of times the plant is started up should be kept to a minimum.

Ash – volume and composition (cases L to O)

In the base case the volume of ash produced is assumed to be 8.199g per kg (or 1,432g/m^3) of wood feedstock. This equates to 1.98g per MJ of electricity produced and is considered reasonably accurate. Different types of feedstock and varying gasification conditions will produce different quantities of ash. Therefore two sensitivities were chosen: a 50% decrease for the low case L (0.99g); and 100% increase for the high case M (3.96g). The primary effect of these sensitivities was on toxicity and freshwater eutrophication (see Table H-5), with almost no effect (less than 1%) on the other impact categories.

Table H-5: Effect of different volumes of ash on freshwater eutrophication and toxicity categories

Impact Category	Unit	Base case (kg per GJ)	Sensitivity Case (% change from base case)	
			L – low ash	M – high ash
freshwater eutrophication	kg P eq	0.02	-49%	98%
human toxicity	kg 1,4-DB eq	1.33	-19%	38%
terrestrial ecotoxicity	kg 1,4-DB eq	2.66	-50%	100%
freshwater ecotoxicity	kg 1,4-DB eq	2.21	-49%	99%
marine ecotoxicity	kg 1,4-DB eq	0.29	-44%	89%

The composition of ash (case N) was also found to primarily impact upon the toxicity impact categories. To assess the effect of a different ash composition, Willow ash and Miscanthus ash data (see Table H-6) was obtained from IEA Bioenergy Task 32 (IEA, 2010). Both datasets were input into SimaPro and assessed using ReCiPe (midpoint). Results for both ash compositions were found to only effect freshwater eutrophication and the four toxicity categories.

For Willow ash the main findings showed that when Phosphate is not present in the ash, both terrestrial eutrophication and terrestrial ecotoxicity are reduced by almost 100%. Human toxicity increases drastically where Chlorine, Cadmium, Copper, Zinc, Lead and Arsenic are present in the ash. Freshwater ecotoxicity was found to be reduced by 29% due in part to phosphate but offset primarily by the presence of Chlorine. Marine ecotoxicity only reduced by 2%, again Phosphate and Chlorine were the main determining elements.

Miscanthus ash followed similar patterns but with less variation in the impact categories due to a more similar ash composition to wood. The data used for the composition of ash took the average of a range of samples obtained in IEA Bioenergy Task 32. Whilst this may not necessarily reflect the actual composition of ash of any given gasification system, it does generate some useful findings:

- Phosphate found in the ash has a considerable impact on freshwater eutrophication, and ecotoxicity (terrestrial, freshwater and marine);
- Arsenic, Cadmium, Chlorine, Copper Lead and Zinc found in the ash all have a substantial effect on the 4 toxicity categories.

Table H-6: Typical composition of ash for Wood, Willow & Miscanthus (source: ECN, 2009; IEA 2010)

Element	Symbol	Wood ash mg/kg db	Willow ash mg/kg db	Miscanthus ash mg/kg db
Organic Carbon	-	600	-	-
Sulphur	S	23,800	71,810	8,513
Chlorine	Cl	-	81,537	-
Silicon	Si	121,000	56,941	330,061
Calcium	Ca	225,000	140,585	53,610
Magnesium	Mg	35,900	17,233	15,078
Potassium	K	33,000	142,170	106,312
Sodium	Na	10,000	8,363	1,262
Phosphate	P	19,800	-	8,730
Aluminium	Al	54,500	826	5,823
Iron	Fe	17,000	-	6,998
Copper	Cu	124	305	30
Zinc	Zn	559	20,407	226
Arsenic	As	-	16	30
Nickel	Ni	123	-	30
Chromium	Cr	243	-	30
Lead	Pb	316	5,393	30
Cadmium	Cd	-	124	0

Some studies suggest that ash produced from biomass gasification is inert, so does not react with other elements. Case O therefore assumes that ash is inert and therefore ash does not have an impact on the LCIA results. In this situation freshwater eutrophication is reduced by 98% to less than 1g P eq. per GJ (of electricity produced); terrestrial ecotoxicity falls by almost 100% to less than 1g 1,4-DB eq. per GJ; freshwater ecotoxicity decreases by 99% to 28g 1,4-DB eq. per GJ; and marine ecotoxicity is reduced by 89% to 33g 1,4-DB eq. per GJ. There are also examples of ash produced from bioenergy production being used as a fertiliser for crops. This can lead to an environmental benefit as the ash restores nutrient value to the soil. It was not possible to model this using LCA due to insufficient data.

Water use and waste water (cases P to S)

For the base case a global average was used for the inventory to deliver 1 litre of water to the plant. This had various inputs (including energy use at 0.390 kWh/m^3) and different emissions. Data which was more specific to the South West was found for the sensitivity case P. Wessex water provided data on the energy use and greenhouse gas emissions associated with delivering 1 litre of water. Data was also obtained on the breakdown of energy consumed. Energy consumed in delivering 1 m^3 (1,000 litres) was found to be 0.585 kWh/m^3; the energy mix per GWh was non-renewable UK grid (76.3%), self-produced biogas (11.9%), oil (4.7%), renewable UK grid (4.4%) and others (2.7%) (Wessex Water, 2010). This data and the greenhouse gas emissions were applied to the sensitivity for regional water delivery; other inventory data was kept the same. It was found to have a very minimal effect the results (less than 0.4% change in all impact categories).

Waste water treatment data was also obtained from Wessex water which again provided more specific data for the South West. It was found that 0.984 kWh of UK grid electricity were required to treat 1m^3 of waste water; other data could not be obtained so were kept the same. Sensitivity case Q was therefore for regional data on waste water treatment. The results showed a very small reduction in each impact category (less than 1.1%) due to the lower electricity used in treating waste water in the South West.

An alternative data source was used to assess a different waste water composition (case R). The data obtained from (SFOE, 1998) was input into the LCI (see Table H-7).

Table H-7: Substances included in waste water inventory for sensitivity case R (source: SFOE, 1998)

Group	Substance	Concentration in waste water (mg/l)
Simple alcohols	Methanol	64
	Ethanol	26
Carboxylic acids	Acetate	30
	Formic acid	-
Simple phenols	Phenol	-

Using the data from SFOE (1998) was found to reduce the impact of freshwater ecotoxicity by 9%. The biggest difference was found to arise from formic acid, followed by phenols, and methanol. The base case assumes that only water is used to scrub the gas, nonetheless different scrubbing fluids (case S) can be used to clean the gas and remove contaminants. Within the scrubbing process, soda (NaOH) is added to get rid of hydrogen sulphide (H_2S) and hydrogen chloride (HCl). Similarly, sulphuric acid (H_2SO_4) is added to remove ammonia (NH_3), carbon disulfide (CS_2) and hydrogen cyanide (HCN). The amounts of H_2SO_4 and NaOH added were adapted from the LCI inventory for a fixed-bed gasifier in Ecoinvent: H_2SO_4 (0.839g/m^3 of producer gas) and NaOH (3.335g/m^3 of producer gas) (Jungbluth *et al.*, 2007). Unfortunately it was not possible to properly model this due to insufficient inventory data on emissions being available. Instead the impacts of the production of soda and sulphuric acid were assessed and found to contribute most notably towards the toxicity categories and freshwater eutrophication.

Producer gas combustion emissions and legislation (case T)

To assess the effect of different levels of producer gas combustion emissions (case T), a review of different emissions legislation was completed. Five different emission limits were obtained for comparison from Denmark, Germany, UK, USA, and the EU. Each of these is summarised in Table H-8.

Table H-8: Emission limits for producer gas combustion in Denmark, Germany, UK, USA, and the EU

Country / Region	Emission	Emission limit value	Reference
Denmark	Nitrogen Oxides (NO_x)	550mg/m³	IEE, 2009b
	Polycyclic Aromatic Hydrocarbons (PAH)	1500mg C/m³	
	Carbon monoxide (CO)	3000mg/m³	
Germany	Carbon monoxide (CO)	650mg/m³	TA Luft, 2002.
	Nitrous Oxide (NO_x), stated as NO_2	500mg/m³	
	Formaldehyde (HCOH)	60mg/m³	
	Benzene	1mg/m³	
	Dust	20mg/m³	
UK	Carbon monoxide (CO)	150mg/m³	Environment Agency, 2004
	Nitrous Oxide (NO_x)	350mg/m³	
	Particulate Matter	20mg/m³	
	Hydrocarbons	20mg/m³	
US (Clear Skies Initative)	Nitrogen Oxides (NO_x)	243mg/m³	Higman & van der Burgt, 2008
	Particulate Matter	485mg/m³	
EU (Waste Incineration Directive)	Total dust	10mg/m³	EU, 2006
	Gaseous and vaporous organic substances, expressed as total organic carbon	10mg/m³	
	Hydrogen chloride (HCl)	10mg/m³	
	Hydrogen fluoride (HF)	1mg/m³	
	Sulphur dioxide (SO_2)	50mg/m³	
	Nitrogen monoxide (NO) and nitrogen dioxide (NO_2)	200mg/m³	

Each of the five different emission limits were input to the LCI in SimaPro and calculated to assess the effect on the results. These different emission limit values are the maximum possible permitted in each country or region, and therefore represent the extreme values. It should be noted that this BGP is well within these limits, and so the results presented here are to illustrate the potential effects of higher emissions.

Particulate matter formation increases significantly with all five emission limits due to the higher releases of NO_x, particulates, and sulphur dioxide. Similarly, all were also found to significantly increase the potential for terrestrial acidification, due primarily to the increase in Nitrogen Oxides (NO_x). Marine eutrophication is also significantly increased due to increased releases of NO_x. For the Denmark and Germany emission limits, the impact category human toxicity is directly affected by the release of PAHs and Formaldehyde respectively. Photochemical oxidant formation is influenced by the release of CO, NO_x, and Formaldehyde.

APPENDIX I. TRANSPORTATION LIFE CYCLE INVENTORY

Table I-1: Life cycle impacts for one tonne-km of a 12t lorry operation – LCIAM: ReCiPe (midpoint)

Impact category	Unit	Total	Operation	Lorry Manufacture	Lorry maintenance	Road construction	Road maintenance	Lorry disposal
climate change	kg CO2 eq	2.91E-01	2.55E-01	1.08E-02	6.07E-03	1.58E-02	2.37E-03	3.82E-04
ozone depletion	kg CFC-11 eq	4.54E-08	3.83E-08	8.28E-10	1.11E-09	4.85E-09	2.93E-10	5.14E-12
terrestrial acidification	kg SO2 eq	1.48E-03	1.33E-03	4.29E-05	2.29E-05	7.89E-05	6.34E-06	2.21E-07
freshwater eutrophication	kg P eq	3.74E-06	6.29E-07	1.29E-06	2.73E-07	1.45E-06	8.09E-08	1.02E-08
marine eutrophication	kg N eq	2.76E-04	2.56E-04	4.41E-06	1.44E-06	1.27E-05	1.26E-06	8.01E-08
human toxicity	kg 1,4-DB eq	9.90E-03	3.64E-03	3.31E-03	6.57E-04	1.89E-03	1.66E-04	2.36E-04
photochemical oxidant formation	kg NMVOC	2.49E-03	2.22E-03	4.03E-05	2.16E-05	1.94E-04	6.58E-06	3.57E-07
particulate matter formation	kg PM10 eq	6.35E-04	5.54E-04	2.66E-05	8.14E-06	4.33E-05	2.32E-06	9.43E-08
terrestrial ecotoxicity	kg 1,4-DB eq	3.21E-05	2.71E-05	1.46E-06	1.50E-06	1.73E-06	2.85E-07	9.48E-09
freshwater ecotoxicity	kg 1,4-DB eq	2.89E-04	1.32E-04	4.87E-05	1.15E-05	4.92E-05	3.00E-06	4.48E-05
marine ecotoxicity	kg 1,4-DB eq	3.63E-04	1.92E-04	6.32E-05	1.95E-05	4.86E-05	4.00E-06	3.58E-05
ionising radiation	kg U235 eq	2.50E-02	4.73E-03	2.57E-03	2.58E-03	3.02E-03	1.21E-02	6.42E-06
agricultural land occupation	m2a	8.60E-04	1.44E-04	2.88E-04	2.31E-04	1.36E-04	5.96E-05	3.35E-07
urban land occupation	m2a	3.54E-03	4.06E-04	1.32E-04	3.05E-05	1.66E-04	2.81E-03	5.63E-07
natural land transformation	m2	1.27E-04	9.10E-05	2.35E-06	3.17E-06	2.80E-05	2.02E-06	1.00E-08
water depletion	m3	8.99E-04	3.01E-04	1.30E-04	3.87E-05	3.42E-04	8.57E-05	4.55E-07
metal depletion	kg Fe eq	1.01E-02	1.06E-03	4.95E-03	6.18E-04	3.27E-03	1.96E-04	2.17E-06
fossil depletion	kg oil eq	1.05E-01	8.65E-02	4.00E-03	3.43E-03	1.03E-02	6.81E-04	1.16E-05

Table I-2: GER for one tonne-km of a 12t lorry operation – LCIAM: CED

Impact category	Unit	Total	Operation	Lorry manufacture	Lorry maintenance	Road construction	Road maintenance	Lorry disposal
Non renewable, fossil	MJ-Eq	4.427	3.646	0.170	0.145	0.433	0.029	0.000
Non-renewable, nuclear	MJ-Eq	0.252	0.048	0.027	0.027	0.030	0.119	0.000
Renewable, biomass	MJ-Eq	0.007	0.002	0.002	0.002	0.001	0.001	0.000
Renewable, wind, solar, geothermal	MJ-Eq	0.002	0.001	0.000	0.000	0.000	0.000	0.000
Renewable, water	MJ-Eq	0.048	0.006	0.006	0.005	0.006	0.025	0.000
Total		**4.735**	**3.703**	**0.206**	**0.179**	**0.470**	**0.174**	**0.001**

APPENDIX REFERENCES

Asman, W. A. H., 1992. *Ammonia emission in Europe: updated emission and emission variations*, Report 228471008, National Institute of Public Health and Environmental Protection, Bilthoven.

Bare, J., Norris, G. A., Pennington, D. W., & McKone, T. 2002. "TRACI The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts", *Journal of Industrial Ecology*, vol. **6**, pp. 49-78.

Brand, G., Braunschweig, A., Scheidegger, A, 1998. *Weighting in Ecobalances with the Ecoscarcity Method – Ecofactors 1997*. BUWAL (SAFEL) Environment Series No. 297, Bern.

British Standards Institute, 2005. BS EN 10088-2:2005 *Chemical composition of stainless steels*. BSI, London.

British Standards Institute, 2004. BS EN 10025-3:2004 *Hot rolled products of industrial structural steels*. BSI, London.

Dreyer, L., Niemann, A., & Hauschild, M. 2003. "Comparison of Three Different LCIA Methods: EDIP97, CML2001 and Eco-indicator 99", *The International Journal of Life Cycle Assessment*, vol. **8**, pp. 191-200.

Harrison, R. M., 1999. *Understanding our Environment - An Introduction to Environmental Chemistry and Pollution (Third Edition)*. The Royal Society of Chemistry, Cambridge.

Hauschild, M. & Potting J., 2004. *Spatial differentiation in life cycle impact assessment – the EDIP2003 methodology*. Guidelines from the Danish Environmental Protection Agency, Copenhagen.

IPPC, O. &. I., 1996. Reference Manual. Revised 1996. *IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3. UK Meterological Office, Bracknell.

Jolliet, O., Margni, M., Charles, R. l., Humbert, S. +., Payet, J. +., Rebitzer, G., & Rosenbaum, R. 2003. "IMPACT 2002+: A new life cycle impact assessment methodology", *The International Journal of Life Cycle Assessment*, vol. **8**, pp. 324-330.

Koellner, T. & Scholz, R. 2007. "Assessment of Land Use Impacts on the Natural Environment. Part 1: An Analytical Framework for Pure Land Occupation and Land Use Change", *International Journal of Life Cycle Assessment*, col. **12**, pp. 16-23.

Oliver, T. 2008. "Clean fossil-fuelled power generation", *Energy Policy*, vol. **36**, pp. 4310-4316.

Nemecek, T. & Kagi, T., 2007. *Life Cycle Inventories of Swiss and European Agricultural Production Systems*, ecoinvent report No. 15. Swiss Centre for Life Cycle Inventories: Switzerland.

Steen, B., 1999. A Systematic Approach to Environmental Priority Strategies in Product Development (EPS). Version 2000 – General System Characteristics. Chalmers University of Technology, Centre for Environmental Assessment of Products and material Systems (CPM) Report 1999:4, Gothenburg.

Vassilev, S. V., Baxter, D., Andersen, L. K., & Vassileva, C. G. 2010. "An overview of the chemical composition of biomass", *Fuel*, vol. **89**, pp. 913-933.